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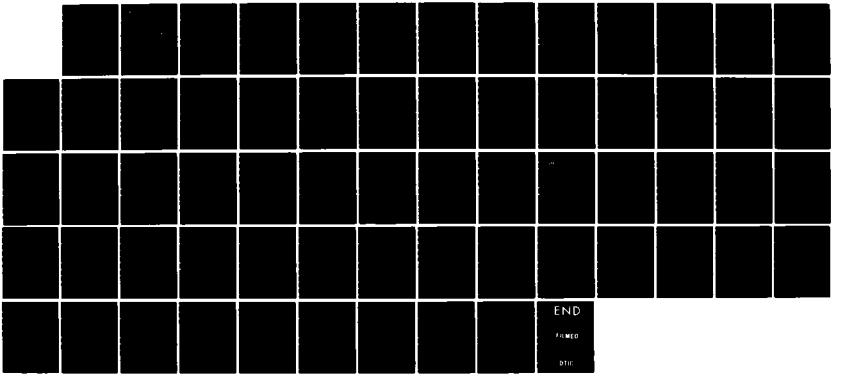

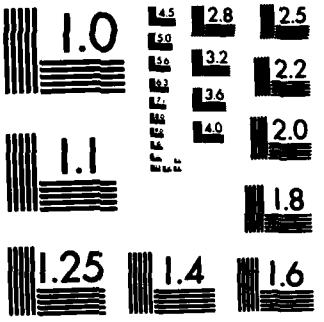

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents an investigation of the stability and control of cascaded doubly fed machines (CDFM). These machines are brushless variable speed constant frequency electric power generators with potential for application in aircraft.

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A previous analytical study indicated the CDFM system would be controllable in the subsynchronous operating mode with a passive RL load. The present study contains two steps. First is an investigation of the machine operation in the supersynchronous mode. The second step is an investigation of machine operation with output capacitors providing excitation VARS for the machine and load.

Step 1 results show that the machines exhibit stability characteristics in the supersynchronous mode similar to those observed in the subsynchronous mode. Step 2 results show that output capacitors degrade the system performance, particularly at light loads. The results show that output current feedback can be employed to improve the system performance.

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Control of Cascaded Induction Generator Systems

Annual Technical Report

By

T.H. Ortmeyer

Department of Electrical and Computer Engineering

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Potsdam, New York 13676

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INTRODUCTION

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MATTHEW J. KERPER
Chief, Technical Information Division

Cascaded doubly fed machines have been shown to have potential for application in aircraft electric power systems. An initial investigation of the steady state performance of these machines [1] predicted their ability to perform as a brushless variable speed constant frequency generator, with competitive weight and cost and the potential for high reliability.

The basic system layout is shown in Figure 1. The machines have multi-phase AC windings on both the stator and rotor. Excitation for the main machine rotor is provided by the exciting machine. The stator of the exciting machine is supplied by a solid state power converter connected to a shaft driven permanent magnet machine, which provides stand alone capability. As direct currents cannot be induced onto the rotor, the main machine must be operated strictly above or below synchronous speed. When using conventional machine analysis during supersynchronous operation, negative frequencies occur [2]. These negative frequencies complicate the analysis of the supersynchronous operating mode. An investigation of machine stability in the subsynchronous operating mode [3] showed that the machine damping could be improved by feedback of the field currents to simulate an increased field resistance. With the analytical model used, the resistance simulation provided stability and good response. Subsequent laboratory tests of the steady state [4] and dynamic state [5] have shown the validity of the analysis.

The purpose of this project has been to analyze the dynamic operation of the machines to provide understanding in two particular areas: first, the machine characteristics in supersynchronous operation; and secondly, the affect of capacitance connected at the machine output on the dynamic performance. The report is divided into two main sections which represent these two goals. Each

section begins with a derivation of the model required for the analysis. In both cases, the model was used for linearized analysis and nonlinear time domain simulation. The results acquired from the analysis and resulting conclusions, are presented in each section. The final computer programs are listed in the appendix, with brief descriptions.

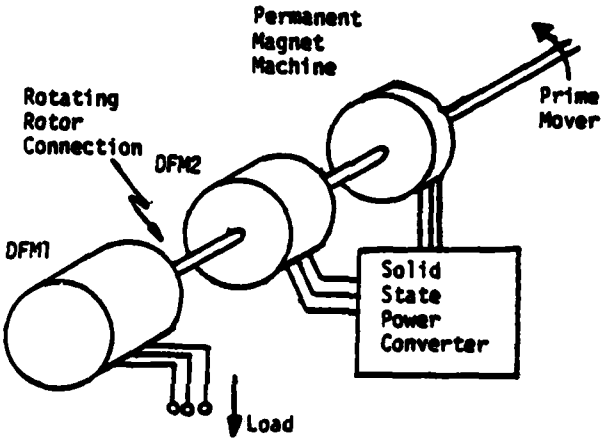


Figure 1. Stand-alone brushless variable speed constant frequency generator system using doubly fed (DFM).

Step 1: Supersynchronous Operation.

a) Analysis

The analysis of the two doubly fed machines is based on the two axis theory of machines [6]. The definitions for the reference frames for each machine are shown in Figure 2. In this figure, the main, or output, machine is designated as machine M1, and the exciting machine is designated as M2. The reference frame speed is defined as

$$p\Theta = \omega_e = \text{nominal output frequency, electrical rad/sec} \quad (1)$$

with respect to the stator magnetic axis. $p(\cdot)$ is defined as the derivative operator $d(\cdot)/dt$, ω_e is the synchronous speed of this machine. The stator transformation from three phase quantities to axis quantities

$$P_s = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos\theta & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta-\frac{2\pi}{3}) & -\sin(\theta+\frac{2\pi}{3}) \end{bmatrix} \quad (2)$$

Similarly, rotor transformation is P . The resulting machine equations are:

$$v_{ds} = r_s i_{ds} + p\lambda_{ds} - \omega_e \lambda_{qs}$$
$$v_{qs} = r_s i_{qs} + p\lambda_{qs} + \omega_e \lambda_{ds}$$
$$v_{dr} = r_r i_{dr} + p\lambda_{dr} - (\omega_e - \omega_r)\lambda_{qr}$$
$$v_{qr} = r_r i_{qr} + p\lambda_{qr} + (\omega_e - \omega_r)\lambda_{dr}$$

where

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr}$$
$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr}$$
$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds}$$
$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs}$$

During normal steady state operation, the machine output frequency is ω_e radians per second, and the rotor frequency, or slip frequency is

$$p\beta = \omega_s \quad \text{radians/second} \quad (5)$$

In this case, the stator and rotor axis voltages and currents are slowly

changing quantities with constant steady state values. The rotor speed is

$$\omega_r = \frac{P_1}{2}\omega_m = \dot{\alpha} \tag{6}$$

where P_1 is the number of poles of machine 1. Therefore, the slip frequency is

$$\omega_s = \omega_e - \omega_r \tag{7}$$

with ω_s being positive for subsynchronous operation and negative for supersynchronous operation.

As the armature of M2 is on the rotor, the primary reference point for the d and q axis is the rotor winding. The armature electrical frequency, rotor speed, and slip frequency are

$$\omega_{e2} = \dot{\eta}$$

$$\omega_{r2} = \frac{P_1}{2}\omega_m = \dot{\gamma} \tag{8}$$

$$\omega_{s2} = \omega_{e2} - \omega_{r2} = \dot{\varepsilon}$$

all in electrical radians per second. The angle definitions are given in Figure 2, and P_2 is the number of poles of machine 2. The phase axis transformations for this machine are P_η and P_ε for the armature and field, respectively, and the electrical quantities are slowly changing variables when the conditions of Eq. 8 are observed.

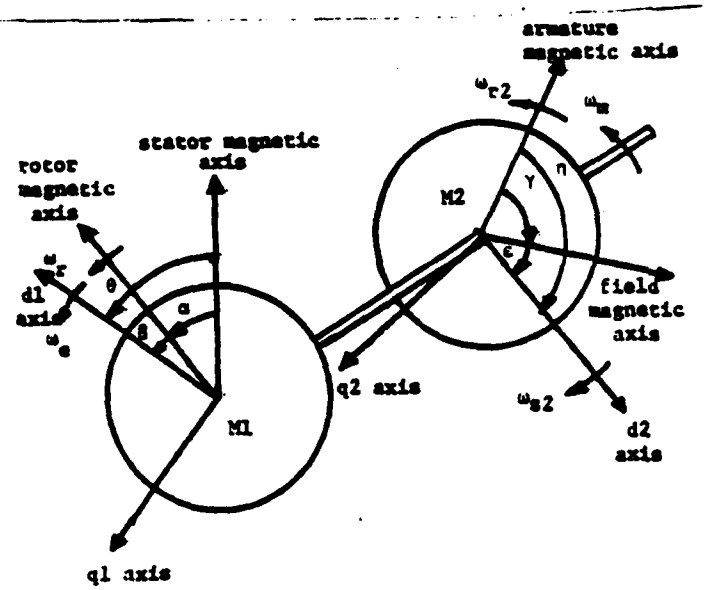


Figure 2. d and q axis reference frame definitions for doubly fed machines M1 and M2.

The resulting machine 2 equations are:

$$\begin{aligned} v_{dA} &= r_A i_{dA} + p\lambda_{dA} - \omega_{e2}\lambda_{qA} \\ v_{qA} &= r_A i_{qA} + p\lambda_{qA} + \omega_{e2}\lambda_{dA} \\ v_{df} &= r_f i_{df} + p\lambda_{df} - (\omega_{e2}-\omega_{r2})\lambda_{qf} \\ v_{qf} &= r_f i_{qf} + p\lambda_{qf} + (\omega_{e2}-\omega_{r2})\lambda_{df} \end{aligned} \tag{9}$$

where

$$\begin{aligned} \lambda_{dA} &= L_A i_{dA} + L_{am} i_{df} \\ \lambda_{qA} &= L_A i_{qA} + L_{am} i_{qf} \\ \lambda_{df} &= L_f i_{df} + L_{am} i_{dA} \\ \lambda_{qf} &= L_f i_{qf} + L_{am} i_{qA} \end{aligned} \tag{10}$$

There exist two independent connections between the phase windings of the rotor of M1 and the rotor of M2. The first of these is

$$\begin{bmatrix} v_{ar} \\ v_{br} \\ v_{cr} \end{bmatrix} = \begin{bmatrix} v_{aA} \\ v_{bA} \\ v_{cA} \end{bmatrix} \begin{bmatrix} i_{ar} \\ i_{br} \\ i_{cr} \end{bmatrix} = \begin{bmatrix} -i_{aA} \\ -i_{bA} \\ -i_{cA} \end{bmatrix} \tag{11}$$

and the rotor reference frame angles are defined as

$$\beta = \eta \tag{12}$$

In this case, the d and q axis quantities are

$$\begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} v_{dA} \\ v_{qA} \end{bmatrix} \tag{13}$$

$$\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} = -\begin{bmatrix} i_{dA} \\ i_{qA} \end{bmatrix}$$

This connection is practical only for subsynchronous operation.

The a phase connection can be assumed to be the same for the second type of connection.

$$\begin{bmatrix} v_{ar} \\ v_{br} \\ v_{cr} \end{bmatrix} = \begin{bmatrix} v_{aA} \\ v_{cA} \\ v_{bA} \end{bmatrix} \cdot \begin{bmatrix} i_{ar} \\ i_{br} \\ i_{cr} \end{bmatrix} = \begin{bmatrix} -i_{aA} \\ -i_{cA} \\ -i_{bA} \end{bmatrix} \tag{14}$$

With reference frame definition

$$\beta = -n \tag{15}$$

the d and q axis equations will be

$$\begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} v_{dA} \\ -v_{qA} \end{bmatrix} \cdot \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} = \begin{bmatrix} -i_{dA} \\ i_{qA} \end{bmatrix} \tag{16}$$

This second type of connection is practical only for the supersynchronous operating mode. Note that ω_{e2} is positive for all practical operating conditions. These connections are practical as they minimize the ratio of field power to output power.

Assuming that the practical connection is used for each mode, Equations 13 and 16 can be written as

$$
\begin{aligned}
v_{dr} &= v_{dA} \\
i_{dr} &= -i_{dA} \\
v_{qr} &= C_s\, v_{qR} \\
i_{qr} &= -C_s\, i_{qA}
\end{aligned}
\tag{17}
$$

where

$$
\begin{aligned}
C_s &= 1 \text{ subsynchronous operation} \\
&\quad -1 \text{ supersynchronous operation}
\end{aligned}
\tag{18}
$$

By interconnecting the rotor windings, two constraints are placed on the system, and two of the eight equations in (3) and (9) must be eliminated. By combining the rotor equations and maintaining i_{dr} and i_{qr} as state variables, the system equations become:

$$v_{ds} = r_s\, i_{ds} + L_s p i_{ds} + L_m\, p i_{dr} - \omega_e\, (L_s i_{qs} + L_m i_{qr})$$

$$v_{qs} = r_s\, i_{qs} + L_s p i_{qs} + L_m p i_{qr} + \omega_e\, (L_s i_{ds}\ \ L_m i_{dr})$$

$$
\begin{aligned}
0 &= (r_r + r_A) i_{dr} + (L_r + L_A)\, p i_{dr} + L_m\, p i_{ds} - L_{Am}\, p i_{df} \\
&\quad -\omega_s\, L_m\, i_{qs} - \omega_s\, (L_r + L_A)\, i_{qr} + \omega_{e2}\, L_{Am}\, i_{qf}
\end{aligned}
\tag{19}
$$

$$
\begin{aligned}
0 &= (r_r + r_A)\, i_{qr} + (L_r + L_A)\, p i_{qr} + L_m p i_{qs} - C_s\, L_{am}\, p i_{qf} \\
&\quad + \omega_s\, [L_m i_{ds} + (L_r + L_A) i_{dr} - L_{Am}\, i_{df}]
\end{aligned}
$$

$$v_{df} = r_f i_{df} + L_f\, p i_{df} - L_{Am} p i_{dr} - \omega_{e2}\, (L_f\, i_{qf} - C_s\, L_{Am}\, i_{qr})$$

$$v_{qf} = r_f i_{qf} + L_f\, p i_{qf} \neg C_s L_{Am} p i_{qr} + \omega_{s2}\, (L_f\, i_{df} - L_{Am}\, i_{dr})$$

This set of equations is valid for either subsynchronous or supersynchronous operation. Existing programs for eigenvalue and time simulation were upgraded to include these equations.

The programs assume that the field voltage is aligned with the d2 axis. The specification of initial conditions is done in terms of output terminal quantities (voltage, current power, and frequency) as well as machine speed. This requires the definition of x_1 and y_1 axes for machine 1 and x_2 and y_2 axes for machine 2 which are displaced from the d_1 and d_2 axes by some constant angle. The initial state problem is solved by setting the output voltage on the x_1 axis, solving for the rotor and field currents, and then reflecting these quantities to the d_1, d_2, q_1 and q_2 axes.

The linearized analysis program and the simulation program were developed from this analysis and verified by comparison of solution between the programs.

b) Resistance simulation

Previous studies of subsynchronous operation [3,5] had shown that stability could be provided by feedback of the field currents to simulate increased resistance in the field circuit, thereby providing damping to the system. The feedback equations are

$$\begin{bmatrix} V_{dr} \\ V_{qf} \end{bmatrix} = \begin{bmatrix} V_{ds} \\ 0 \end{bmatrix} - \begin{bmatrix} C_1 & 0 \\ 0 & C_1 \end{bmatrix} \begin{bmatrix} i_{df} \\ i_{qf} \end{bmatrix} \tag{20}$$

V_{df} and V_{qf} are the actual field voltage commands sent to the power converter, and V_{df} is the simulated field voltage. The output voltage is regulated by an integral controller. The basic controller is shown in Figure 3. With assumptions of ideal current and voltage sensing, and an ideal power converter, the feedback quantity C_1 exactly represents increased field resistance. These assumptions are employed in this analysis.

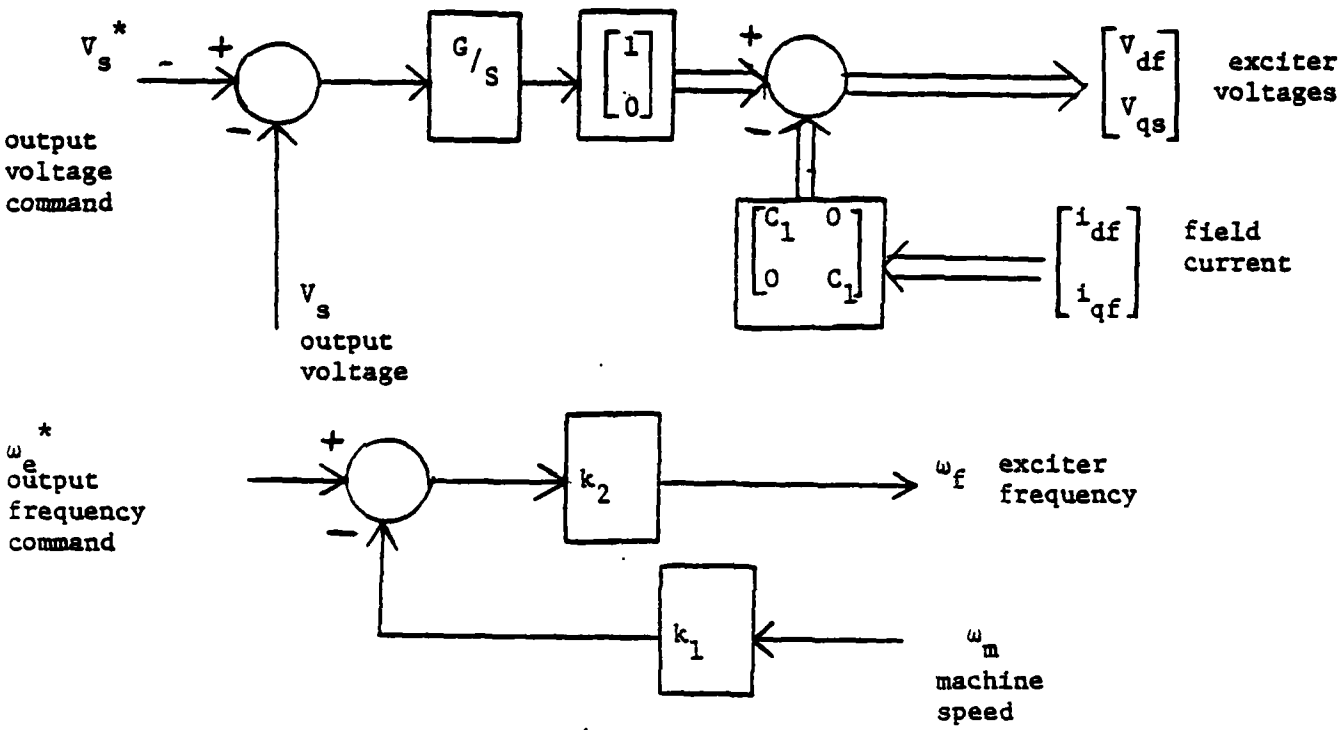


Figure 3. Basic system controller with state feedback of the machine field currents.

C) Results

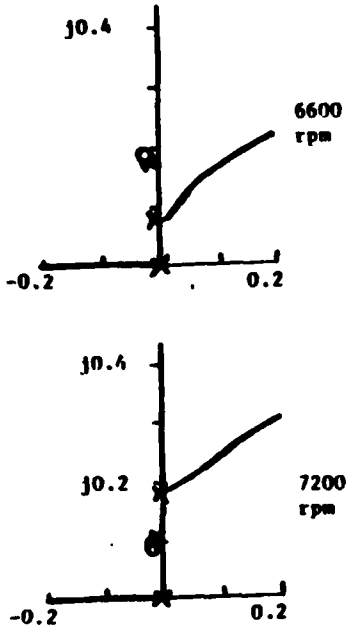
The model given in parts a and b of this section was used to study the controllability of the machines in supersynchronous operation. As the machine control during subsynchronous operation was previously studied, a comparison between these two modes was indicated. For this comparison, the machine constants given in Table I were used. For both the sub- and supersynchronous cases. The cases involve identical machines run over 1.5:1 speed ranges.

The root loci for the machines are given in Figures 4 and 5. These figures show the significant loci in the upper half of the s-plane. Both modes of operation exhibit a complex pole-zero pair, with relatively close coupling of this pole and zero. This pair is associated with the rotor winding of the machines. The second complex pole-zero pair which is shown is related to the field winding of the machines. Figure 4 compares sub- and supersynchronous operation with no state feedback. In all cases, the open loop poles are lightly damped. At low speeds, both cases exhibit a zero in the RHP near the $j\omega$ axis. At high speeds, both systems exhibit a zero far into the RHP. Figure 5 contains the results with resistance simulation feedback $c_1 = 59r_f$. As is true in subsynchronous operation, the feedback successfully moves the open loop pole of the system into the LHP. Additionally, close coupling between the rotor pole-zero pair is obtained. At low speeds, the zero associated with the field is located in the LHP and the system is stable for all integrator gains. As the speed increases, this zero moves into the RHP, and the system becomes unstable at high gain. Figure 5 shows that this movement of the zero occurs at a relatively lower speed in supersynchronous operation than in subsynchronous operation. At the highest speed in subsynchronous operation, the rotor zero moves above the open loop pole, and the field locus crosses the $j\omega$ axis below the rotor pole-zero pair. These events also lead to degraded performance at high gain.

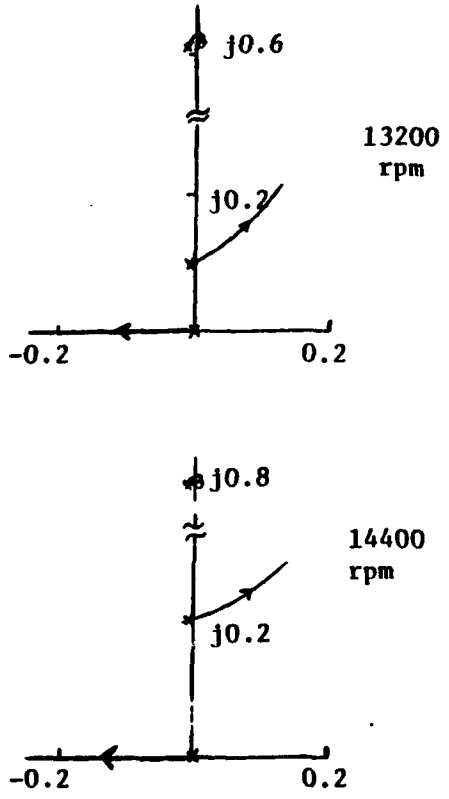
TABLE I

MACHINE CONSTANTS FOR 40 KVA, 400 HERTZ GENERATOR, SUPERSYNCHRONOUS 9600-14400 rpm SPEED RANGE. PER UNIT VALUES GIVEN ARE THE MACHINE BASE.

	Machine 1	Machine 2
kvA	40.0	16.0
poles	6	2
frequency, hz	400	160
stator resistance	0.02 pu	0.025 pu
stator reactance	4.08 pu	4.08 pu
rotor resistance	0.025 pu	0.02 pu
rotor reactance	4.08 pu	4.08 pu
magnetizing reactance	4.0 pu	4.0 pu

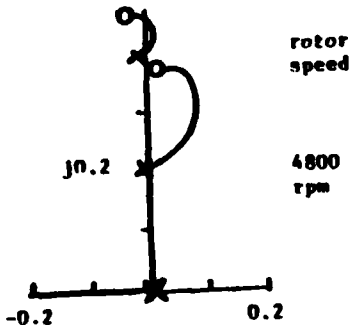


a. subsynchronous operation

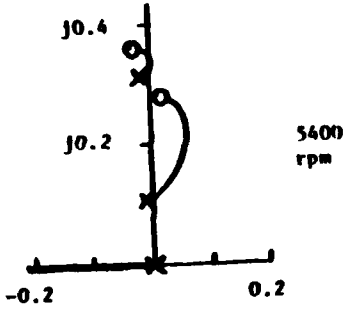


b. supersynchronous operation

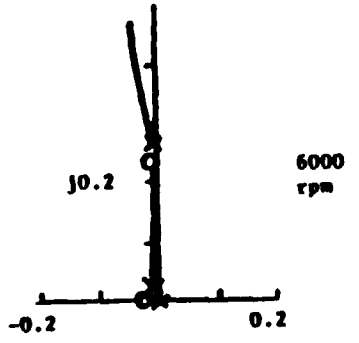
Figure 4. Comparison of sub- and sypersynchronous root loci with no state feedback. Rated output voltage and frequency with loading of 1% of rated power, unity power factor.



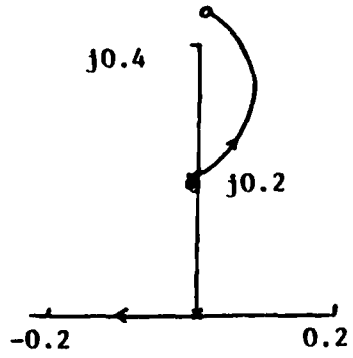
rotor speed 4800 rpm



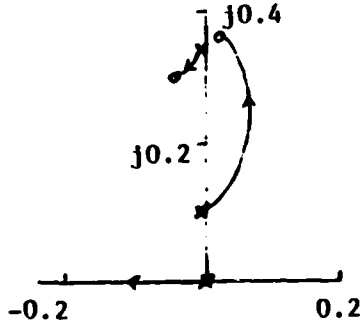
rotor speed 5400 rpm



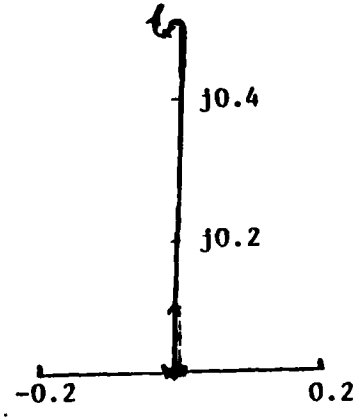
rotor speed 6000 rpm



rotor speed 9600 rpm

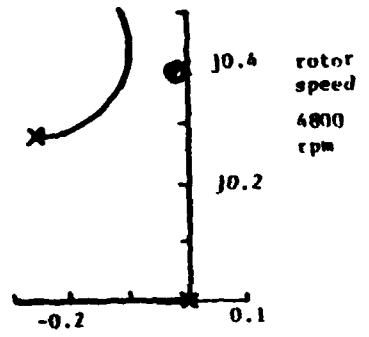


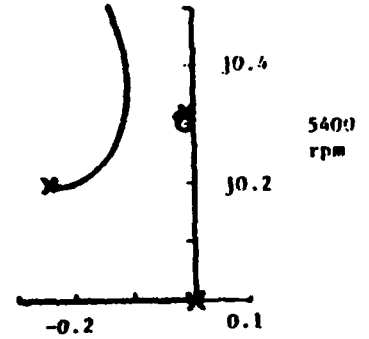
rotor speed 10800 rpm

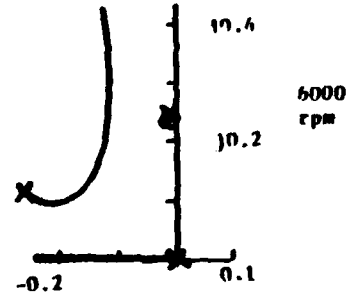


rotor speed 12000 rpm

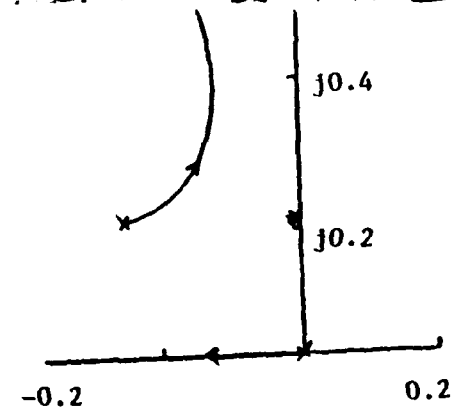
Figure 4. Continued

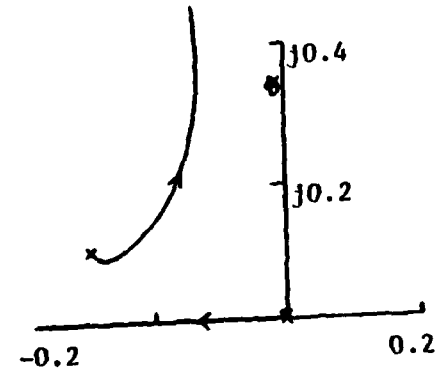


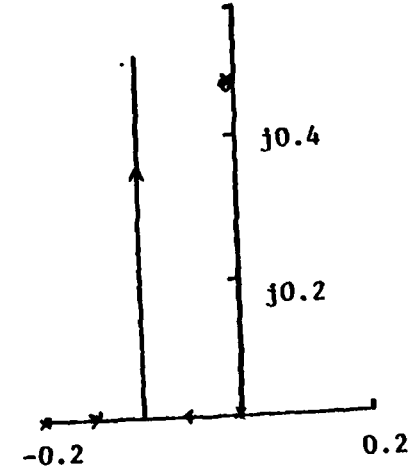




a. subsynchronous operation

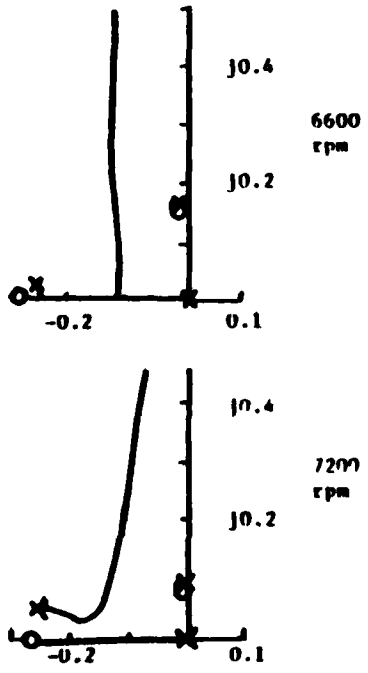




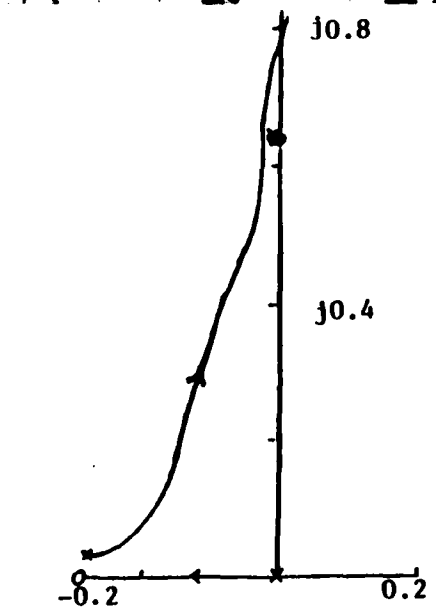


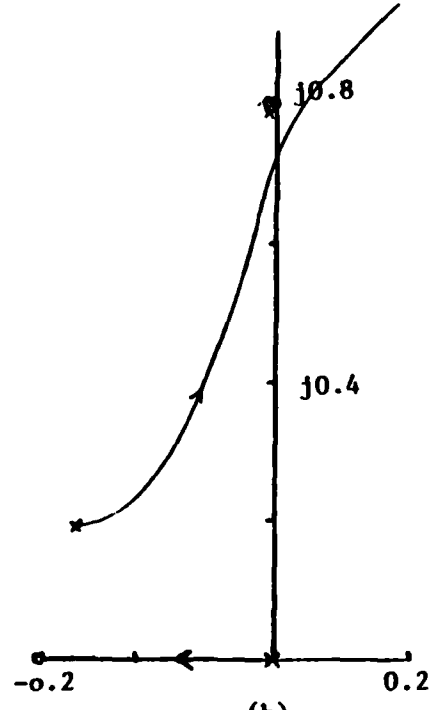
b. supersynchronous operation

Figure 5. Comparison of sub- and supersynchronous root loci with state feedback of field currents, $C_1 = 59r_f$. Rated output voltage and frequency with loading of 1% of rated power, unity power factor.



(a)





(b)

Figure 5 (cont.)

The results show that stability can be obtained by implementing resistance simulation in both the subsynchronous and supersynchronous operating modes. For the case studied, sufficient damping was obtained throughout the speed range of interest to ensure good response. The subsynchronous mode showed slightly better characteristics at high speed, however, and it is possible that the subsynchronous mode could out perform the supersynchronous mode in cases involving a larger speed range. As the advantages of the cascade machine system are most pronounced where small speed ranges are required, and it appears that the sub- and supersynchronous modes of operation are equally controllable for low speed ranges.

Step 2: CDFM controllability with capacitive load

a) Analysis

The inital studies of the cascaded doubly fed machine (CDFM) generator system involved a passive series RL load on the generator. In many applications, however, it would be desirable to place shunt capacitors at the generator terminals to supply the load VARS and a share of the generator system excitation requirements. This would reduce the current flow in the exciter and field.

Step 2 of this project involves a study of the effect of this capacitance on machine stability. The system diagram is shown in Figure 6. The study involves shunt capacitance permanently connected at the generator terminals which supply VARS equal to 66% of the generator rating. The capacitors are permanently connected to the generator to avoid the weight and reliability problems of a switch. The bank rating was chosen from steady state considerations.

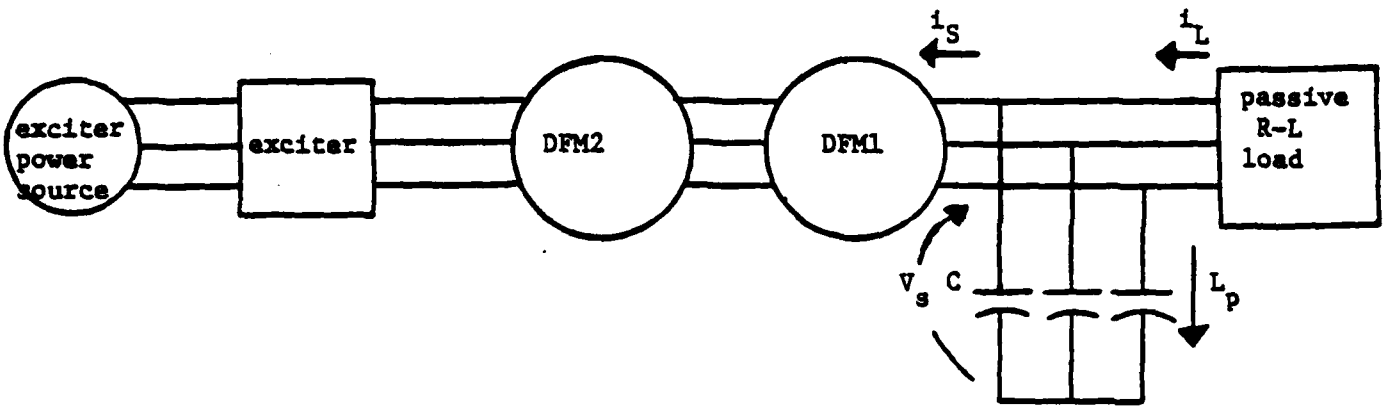


Figure 6. System diagram of the CDFM generator with capacitance supplying excitation VARS. Reference directions for the currents and voltages at the generator output are shown.

The addition of the capacitors will increase the state of the system by four: two for the capacitors and two for the load. The capacitor equations are:

$$\begin{bmatrix} i_{ap} \\ i_{bp} \\ i_{cp} \end{bmatrix} = C \begin{bmatrix} pv_{as} \\ pv_{bs} \\ pv_{cs} \end{bmatrix} \tag{21}$$

and the load equation are:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = L_L \begin{bmatrix} pi_{aL} \\ pi_{bL} \\ pi_{cL} \end{bmatrix} + R_L \begin{bmatrix} i_{aL} \\ i_{bL} \\ i_{cL} \end{bmatrix} \tag{22}$$

When these are transformed by the output winding transformation (Equation 2), the system equations are (neglecting the 0 axis quantities):

$$\begin{aligned} v_{ds} + R_L\, i_{dL} + L_L\, pi_{dL} - \omega_e\, L_L\, i_{qL} &= 0 \\ v_{qs} + R_L\, i_{qL} + L_L\, pi_{qL} + \omega_e\, L_L\, i_{dL} &= 0 \end{aligned} \tag{23}$$

$$\begin{aligned} i_{dP} &= i_{dL} - i_{ds} = C\, pV_{ds} - \omega_e C\, v_{qs} \\ i_{qp} &= i_{qL} - i_{qs} = C_p\, v_{qs} + \omega_e C\, v_{ds} \end{aligned} \tag{24}$$

where i_{dL}, i_{qL}, v_{ds} and v_{qs} have been chosen as the new state variables. The incremental magnitude of the output voltage is:

$$V_{ol} = \frac{v_{dso}}{v_{so}}\, v_{ds_1} + \frac{v_{qso}}{v_{so}}\, v_{qs_1} \tag{25}$$

The initial condition calculations are performed in the same manner as in step 1. The computer programs used to study the system are listed in the appendix. The results are presented in terms of linearized s-plane plots. The time simulation programs were used to validate these results. It has been found that

the system exhibits good time response when the real eigenvalue and the two dominant complex pairs all have negative real parts with magnitude greater than 0.1 pu. The lightly damped pole-zero pair remains closely coupled with the feedback strategies shown, and has negligible effect on the system response.

b) Results - field current feedback

The machines described in Table 1 were used to investigate the effect of output capacitors on system stability. Due to the results of step 1 of the project, only the subsynchronous operating mode was considered.

Figure 7 shows a root locus study of the system with voltage regulator but no state feedback. The dominant poles of the system are shown on the upper half of the per unit s-plane. The system is open loop unstable at the two upper speeds. At low speed, a lightly damped low frequency pole quickly goes into the RHP as controller gain is increased.

Field current feedback for resistance simulation was investigated. The results show that a level of resistance simulation somewhat higher than that employed in step 1 of the research will be effective in stabilizing a loaded system. Figure 8 shows the root locus plot with resistance simulation $C_1 = 2.0$ pu with system loading $S = 1 \angle 41^\circ$ pu, where 1.0 pu represents the rated output KVA of the machine. Figures 9 and 10 shown the same feedback system at lighter machine loads. With $S = 0.25 \angle 5^\circ$, the low frequency loci has shifted to the right, particularly at high machine speeds. With load further reduced, the locus will shift completely into the RHP, as shown in Figure 10. In these cases, the high frequency locus begins well into the LHP and moves into the RHP at very high gains.

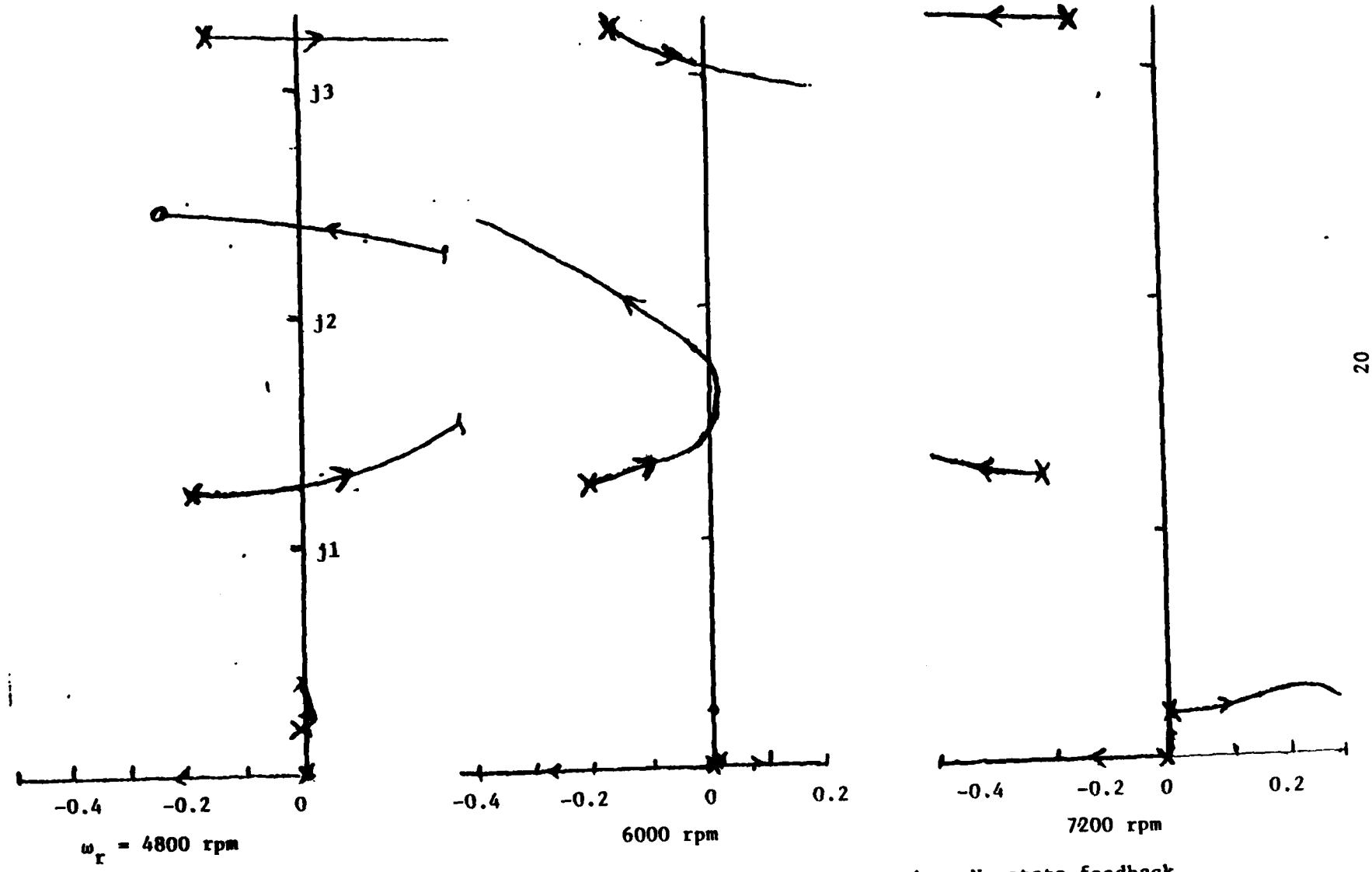


Figure 7. Closed loop pole movement with increasing integrator gain. No state feedback, Light load condition, S = 0.15° pu.

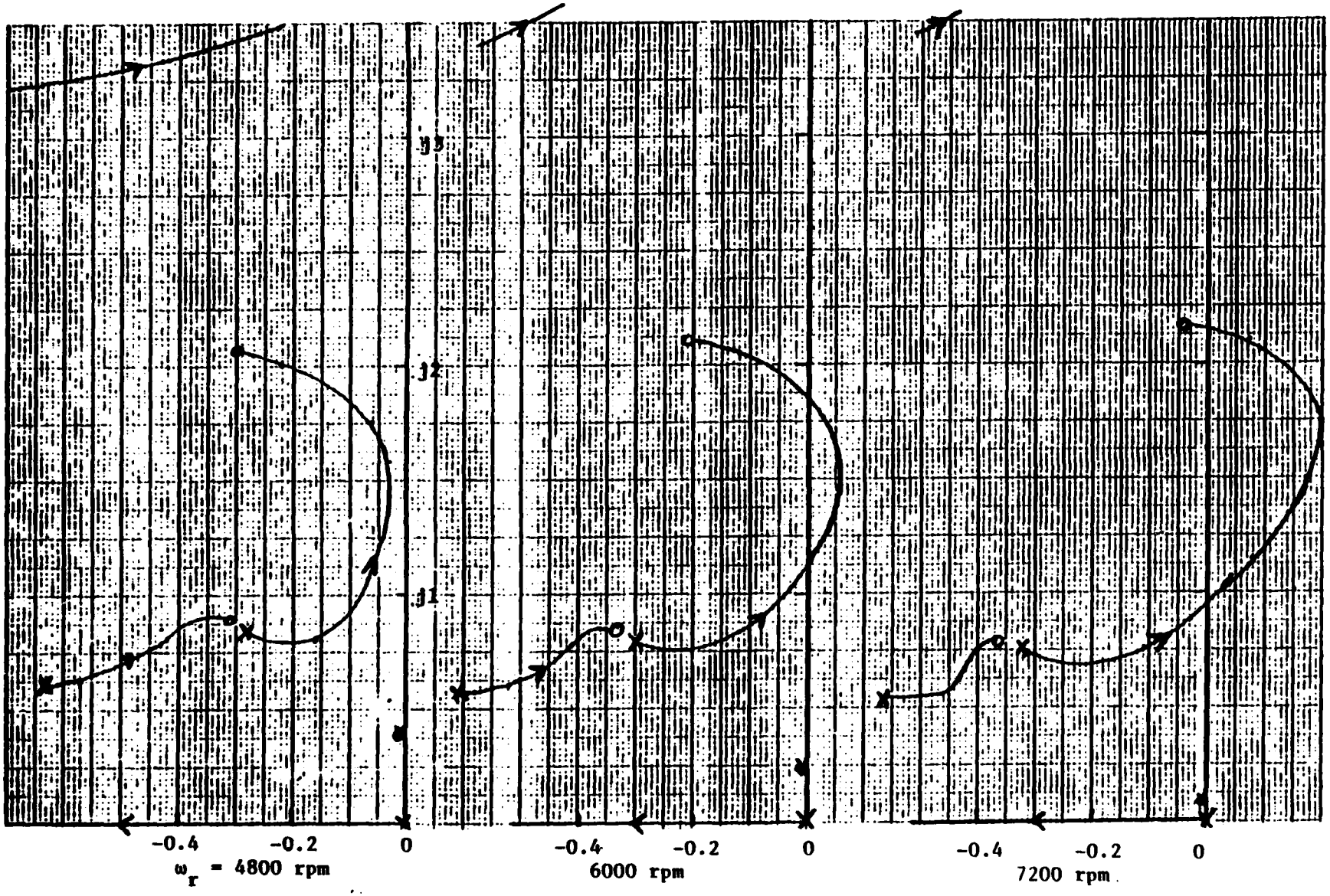


Figure 8. Closed loop pole movement with increasing integrator gain. Rotor current feedback C_1 = 2.0. Full load condition: S = 1.0$\angle 41^\circ$ pu.

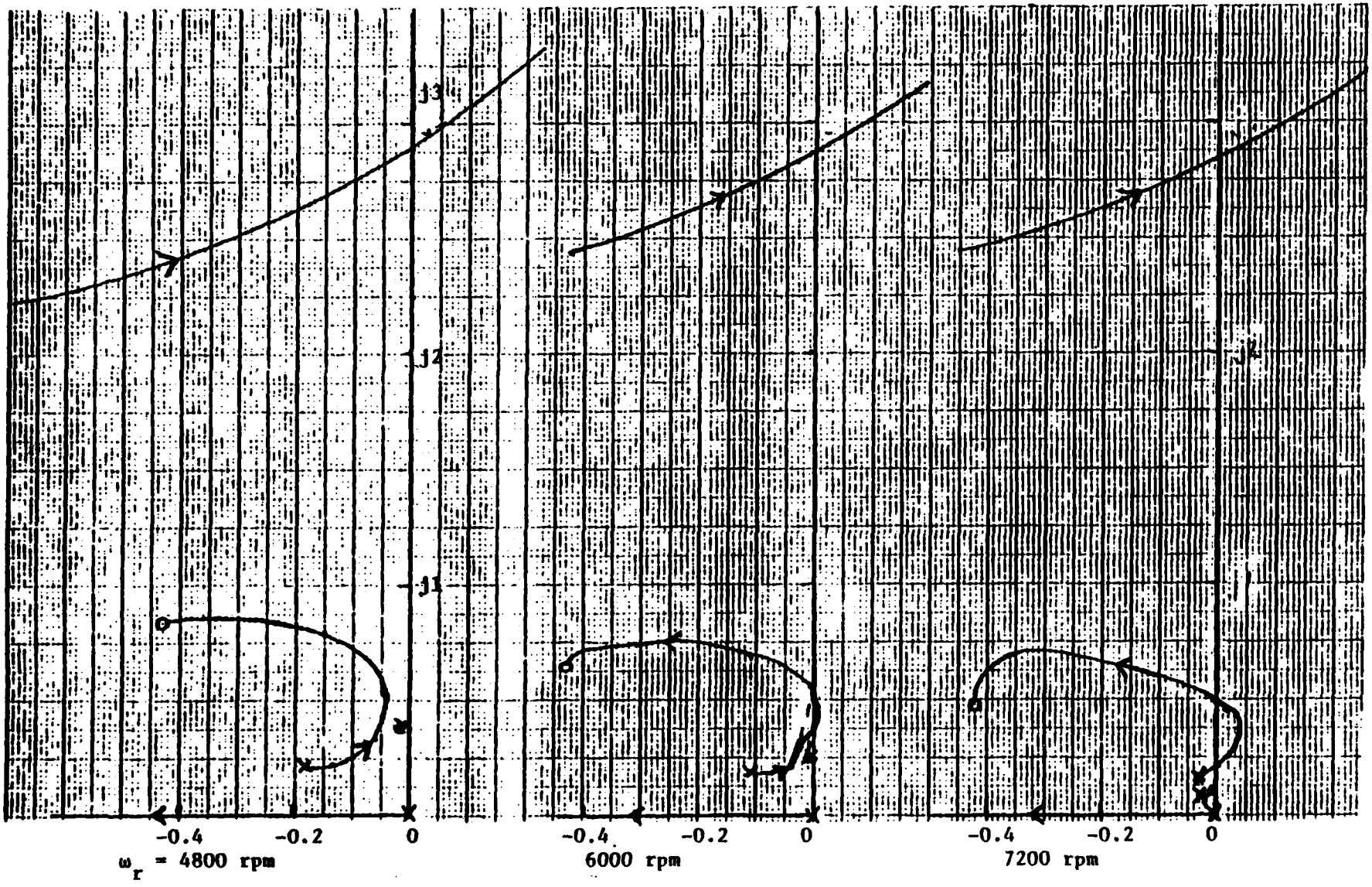


Figure 9. Closed loop pole movement with increasing integrator gai . Rotor current feedback C_1 = 2.0. Medium load condition: S = 0.25$\angle 5^\circ$ pu.

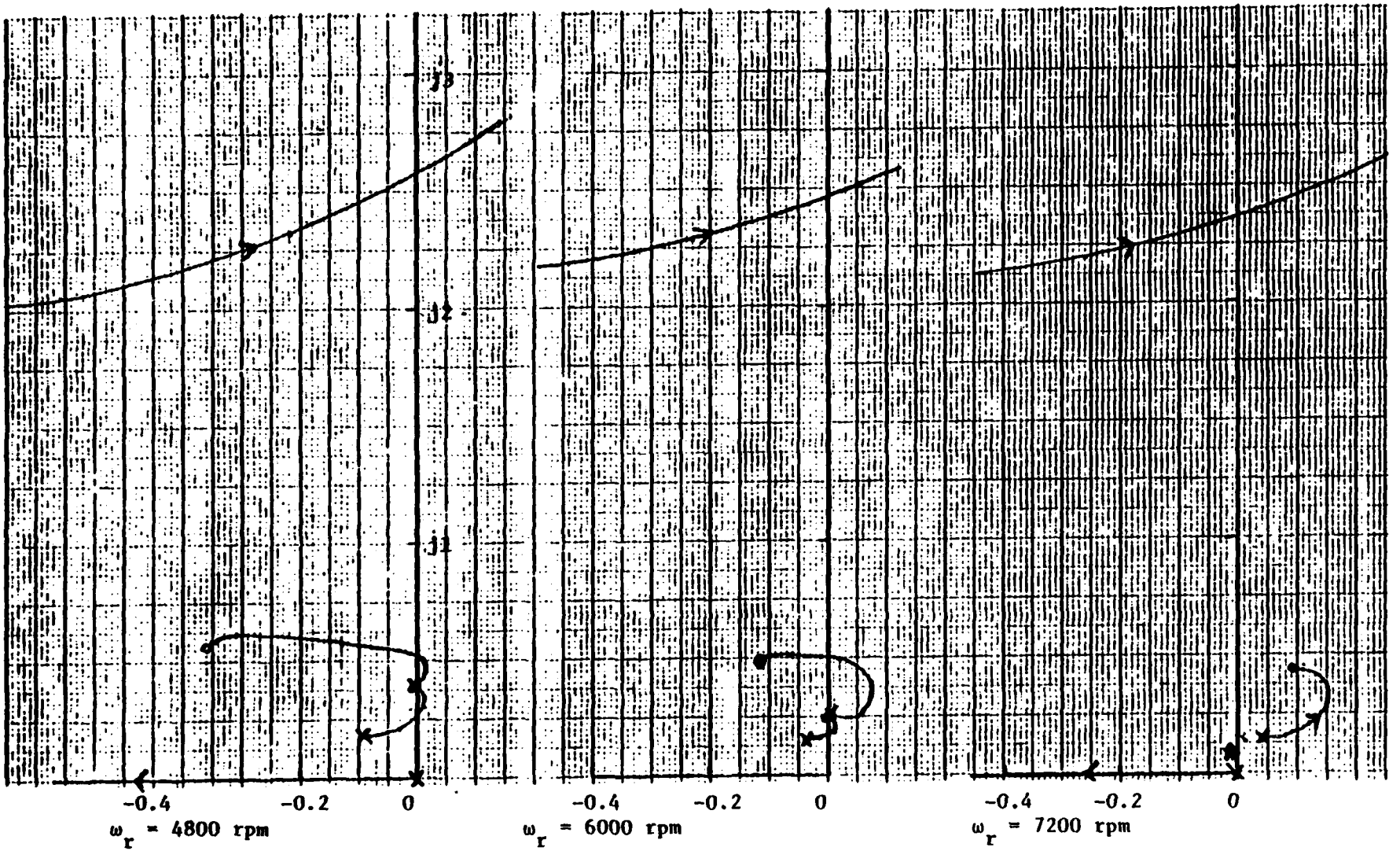


Figure 10. Closed loop pole movement with increasing integrator gain. Rotor current feedback C_1 = 2.0. Light load condition: S = 0.1 $\angle 5^{\circ}$ pu.

The system stability will be studied at light load. $S = 0.1\angle 5^{\circ}$ is chosen, as damping is reduced as the load power factor angle is reduced. Note that, with capacitance, the generator will be operating with low power factor leading current with this load. Figure 11 shows the open loop pole movement for the system as C_1 is varied from 0 to 1 pu. This result shows that resistance simulation alone will not stabilize the system at this load level.

Next studied was the feedback equation

$$\begin{bmatrix} v_{df} \\ v_{qf} \end{bmatrix} = \begin{bmatrix} v_{df} \\ 0 \end{bmatrix} - \begin{bmatrix} C_1 & -C_2 \\ C_2 & C_1 \end{bmatrix} \begin{bmatrix} i_{df} \\ i_{qf} \end{bmatrix} \tag{26}$$

where C_1 is the resistance simulation. C_2 can be expected to provide some level of frequency shifting of the open loop poles [3].

Figure 12 shows the effect of C_2 on the open loop poles of the system. It can be seen that increased C_2 will move the unstable pole into the LHP while causing the previously well damped pole to move toward the RHP. The best response was obtained with $C_1 = 0.2$, $C_2 = 2.25$. The root locus plot with $S=0.1\angle 5^{\circ}$ is shown in Figure 13. While stable operation can be obtained at this loading the response time would be slow, particularly at high speed. Figure 14 shows the result of the increased load, with $S = 0.2\angle 5^{\circ}$. At this load level, stable operation with good response can be obtained. Note that, with $C_1 = 0.2$ and $C_2 = 2.25$, the locus of the high frequency pole initially breaks to the left, while the locus of the low frequency poles breaks to the right. As a result, the placement of the high frequency open loop pole can be much closer to the $j\omega$ axis the placement of the low frequency open loop pole.

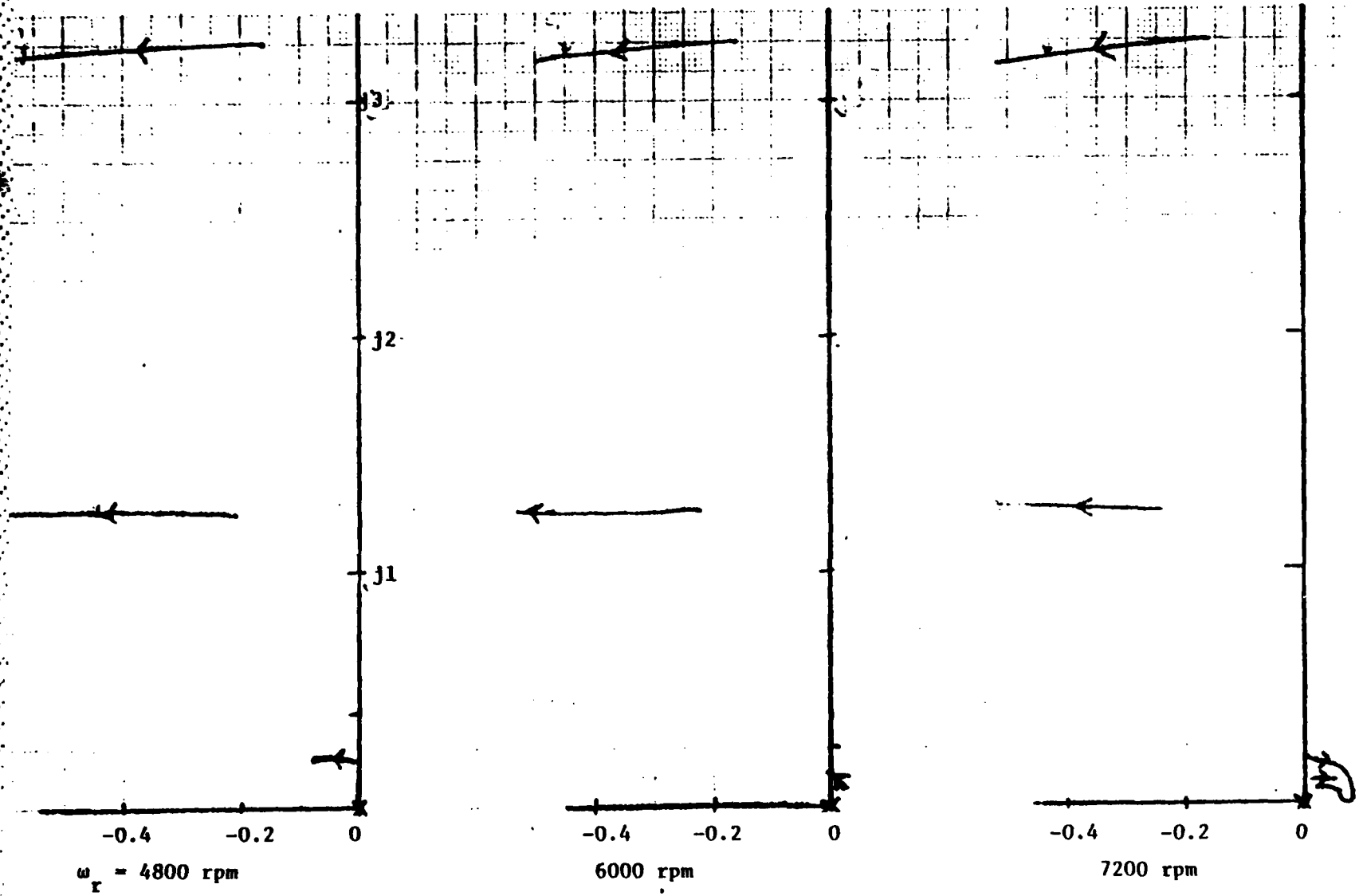


Figure 11. Open loop pole movement with variation rotor feedback parameter C_1. C_1 varied from 0.0 to 1.0 with no other feedback.

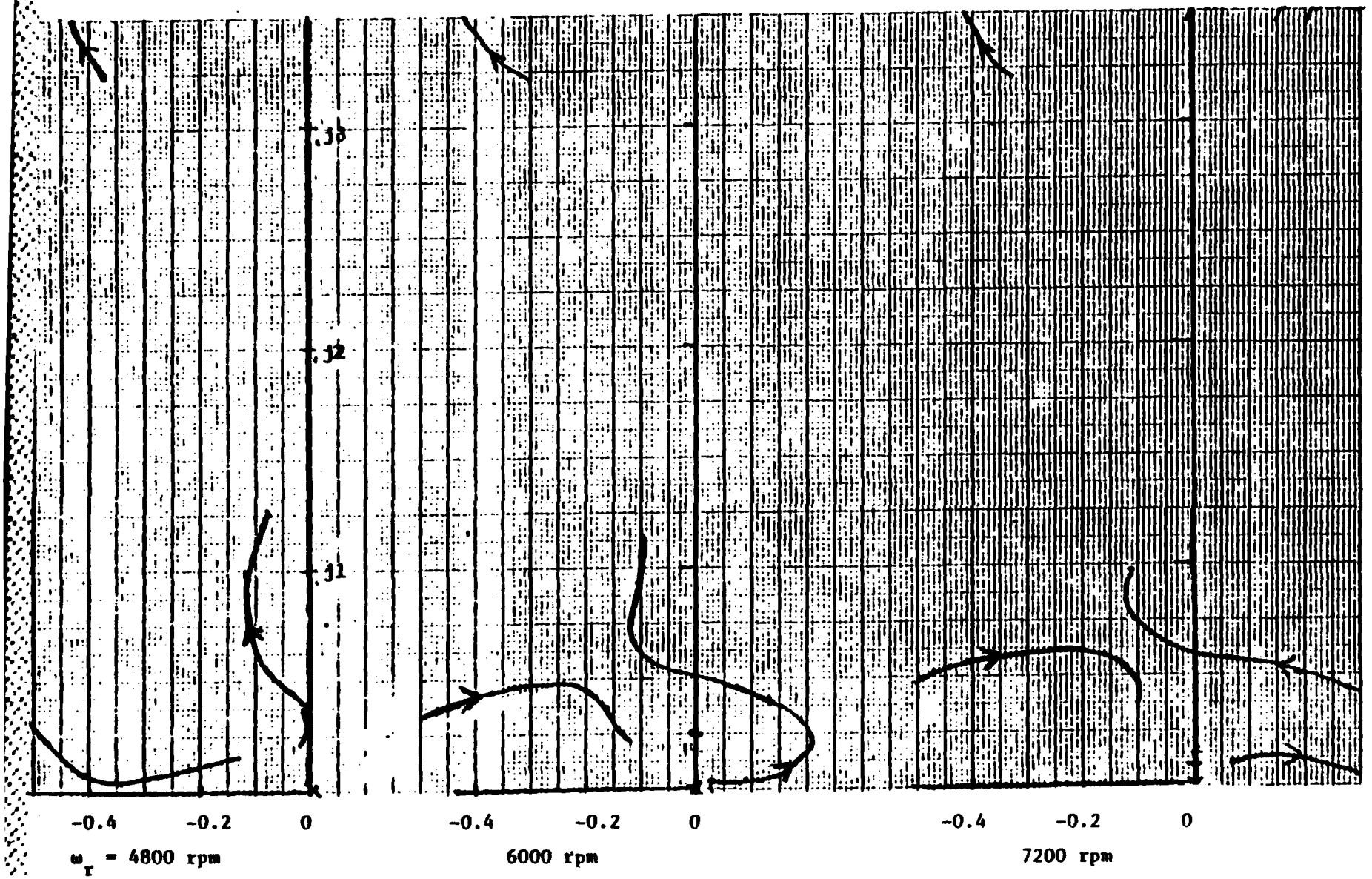


Figure 12. Open loop pole movement with variation of rotor feedback parameter C_2. C_2 increased from 0 to 2.50 with C_1 = 0.2.

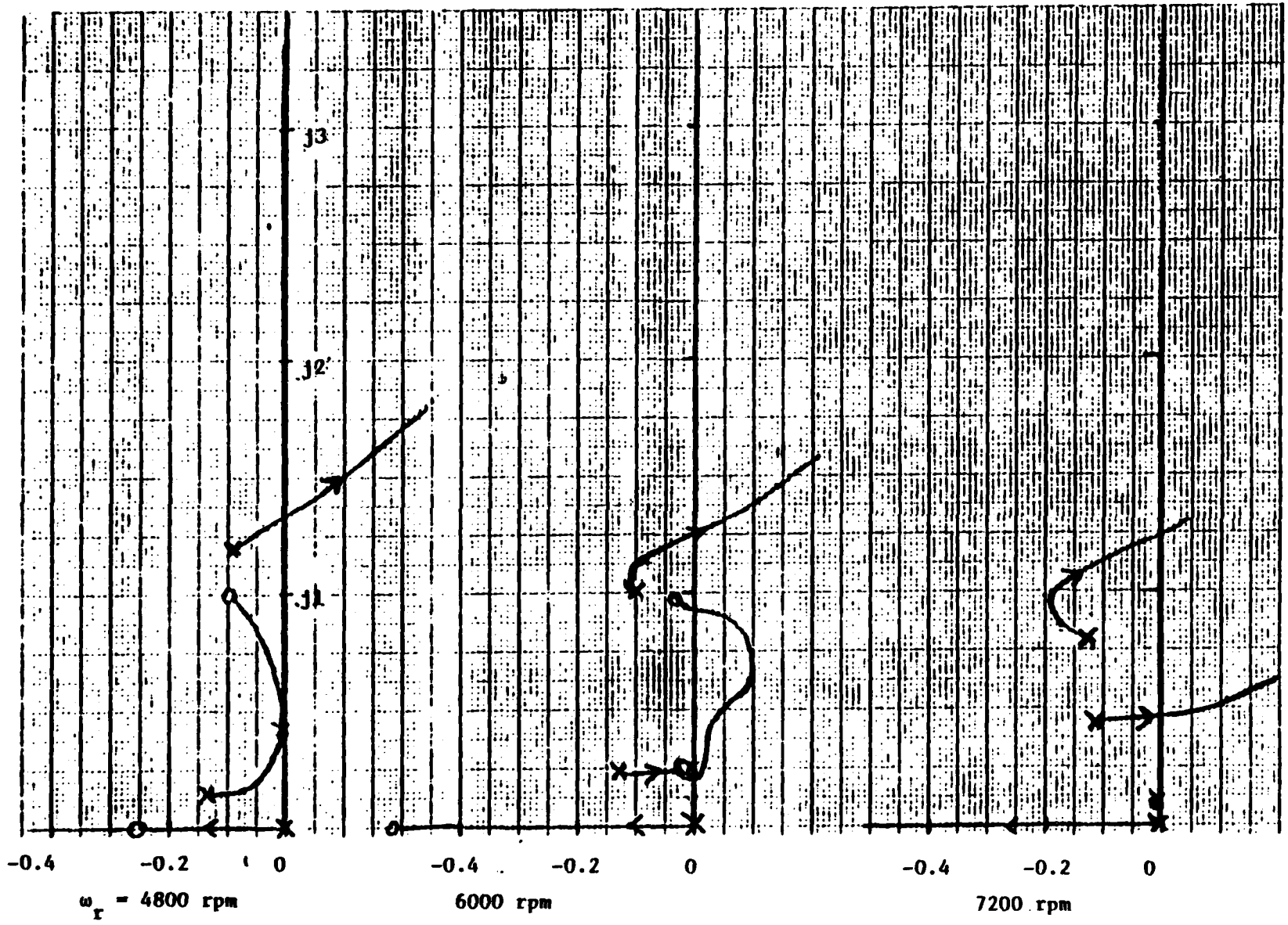


Figure 13. Closed loop pole movement with increasing integrator gain. Rotor feedback parameters $C_1 = 0.2$, $C_2 = 2.25$. System loading S = 0.15 pu.

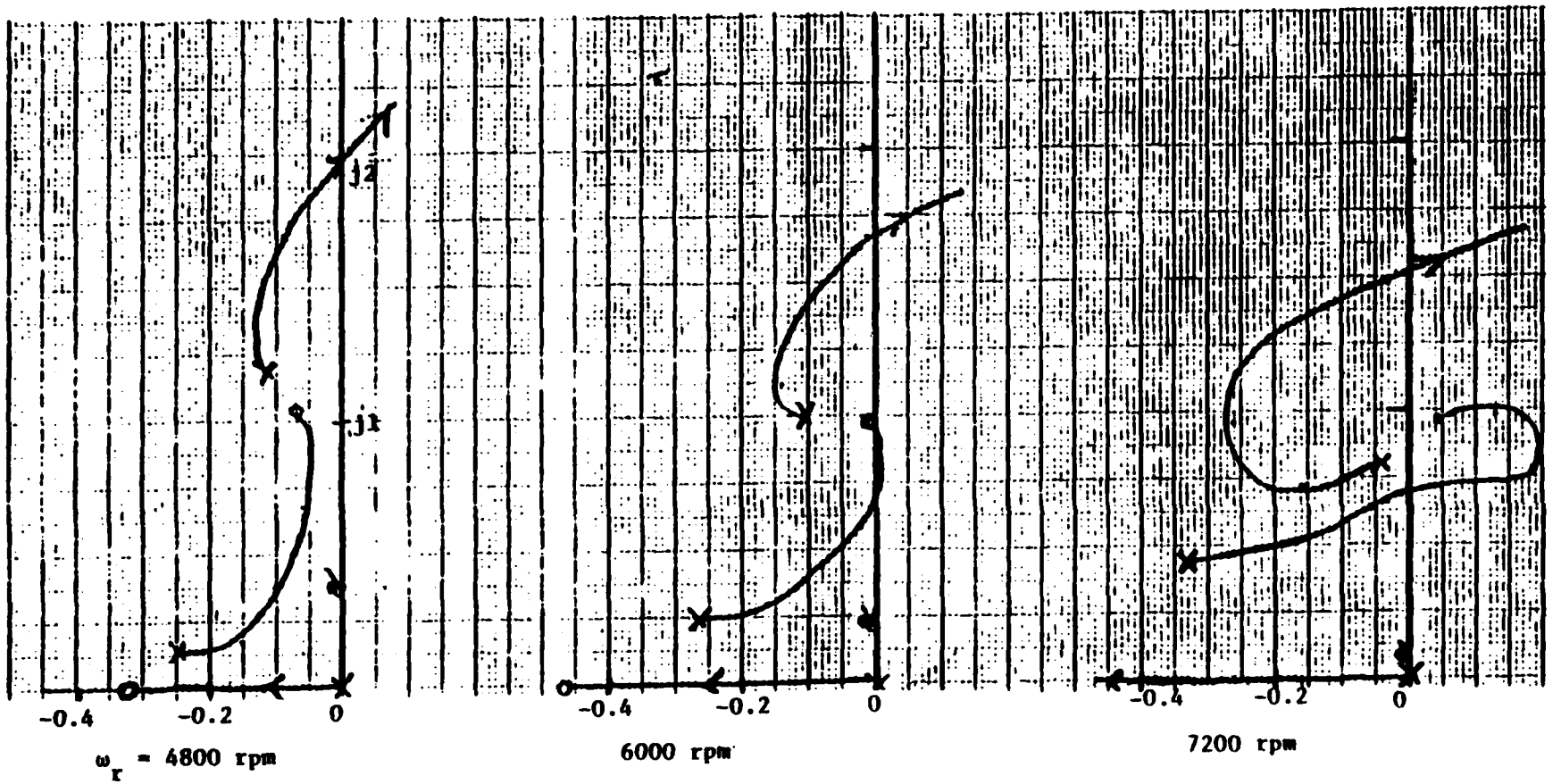


Figure 14. Closed loop pole movement with increasing integrator gain. Rotor feedback parameters $C_1 = 0.2$, $C_2 = 2.25$. System loading at S = 0.2(5° pu.

Due to the poor response at low power levels, the effect of adding feedback from the output of the generator was studied. A number of feedback possibilities were considered. It was considered that feedback of the d and q axis output quantities would be more difficult to implement than feedback of other quantities such as rms current, power, VARS. From the feedback strategies studied, the most successful were:

a) Feedback of capacitor d and q axis current

$$\begin{bmatrix} v_{df} \\ v_{qf} \end{bmatrix} = \begin{bmatrix} v_{df} \\ 0 \end{bmatrix} - \begin{bmatrix} C_1 & -C_2 \\ C_2 & C_1 \end{bmatrix} \begin{bmatrix} i_{df} \\ i_{qf} \end{bmatrix} + C_3 \begin{bmatrix} (i_{dL} - i_{ds}) \\ (i_{qL} - i_{qs}) \end{bmatrix} \tag{27}$$

b) Feedback of machine output current

$$\begin{bmatrix} v_{df} \\ v_{qf} \end{bmatrix} = \begin{bmatrix} v_{df} \\ 0 \end{bmatrix} - \begin{bmatrix} C_1 & -C_2 \\ C_2 & C_1 \end{bmatrix} \begin{bmatrix} i_{df} \\ iqf \end{bmatrix} + C_3 \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \tag{28}$$

c) Feedback of rms output current.

The rms current is

$$I_s = (i_{ds}^2 + i_{qs}^2)^{1/2} \tag{29}$$

and the incremental value is

$$I_{sl} = \frac{i_{dso}}{I_{so}} i_{dsl} + \frac{i_{qso}}{I_{so}} i_{qsl} \tag{30}$$

The feedback equation studied is

$$\begin{bmatrix} v_{df} \\ v_{qf} \end{bmatrix} = \begin{bmatrix} v_{df} \\ 0 \end{bmatrix} - \begin{bmatrix} C_1 & -C_2 \\ C_2 & C_1 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qf} \end{bmatrix} \begin{bmatrix} C_3 \\ C_3 \end{bmatrix} I_s$$

d) Feedback of output power.

The output power is

$$P = -[v_{ds} i_{ds} + v_{qs} i_{qs}] \tag{32}$$

with incremented power

$$P_1 = - v_{dso}\, i_{ds1} - i_{dso}\, v_{ds1} - v_{qso}\, i_{qs1} - i_{qso}\, v_{qs1} \tag{33}$$

For feedback to the d axis,

$$\begin{bmatrix} v_{df} \\ v_{qf} \end{bmatrix} = \begin{bmatrix} v_{df} \\ 0 \end{bmatrix} - \begin{bmatrix} C_1 & -C_2 \\ C_2 & C_1 \end{bmatrix} \begin{bmatrix} i_{df} \\ i_{qf} \end{bmatrix} - \begin{bmatrix} C_3 \\ 0 \end{bmatrix} P \tag{34}$$

Figure 15 shows a comparison of the open loop poles for feedback types a (dq axis capacitor currents) and c (output current magnitude). The field feedback remains at $C_1 = 0.2$ and $C_2 = 2.25$ pu.

Both yield increases in damping at the low frequency eigenvalue, and cause losses in damping at the high frequency eigenvalue. Figure 16 shows the closed loop pole migration for a similar case of capacitor current feedback. The locus diagrams are located well into the left half plane and stable operation with good response is obtained. The dominant eigenvalues at integrator gain of $G_1 = 200$ pu are shown in Table 2.

A study of power feedback (d) is shown in Figure 17. These loci are, for the most part, similar to those seen in Figure 16, and will provide stability with good response with the proper choice of gain. Table 3 lists the dominant eigenvalues for an integrator gain of 200 pu.

It is therefore possible to stabilize the system at light loads by including feedback of an output quantity. Therefore the option of providing output capacitors permanently connected to the generator would appear to be feasible, and should be considered in the design of a CDFM generator system.

Figure 15. Open loop system poles with variation of feedback of stator quantities. Case 4: feedback of rms stator current. Case 5: feedback of d and q axis capacitor currents. In both cases, the stator current feedback parameter C_3 was varied from 0 to 1.8, with rotor current feedback parmeters C_1 = 0.2 and C_2 = 2.25.

TABLE 2

Figure 16. Eigenvalue location at gain of 200 pu.

speed / eigenvalues	4800 rpm	6000 rpm	7200 rpm
	-.16	-.12	-.09
	-.33 ± j.31	-.26 ± j.44	-.22 ± j.60
	-.12 ± j.88	-.12 ± j.84	-.12 ± j.76

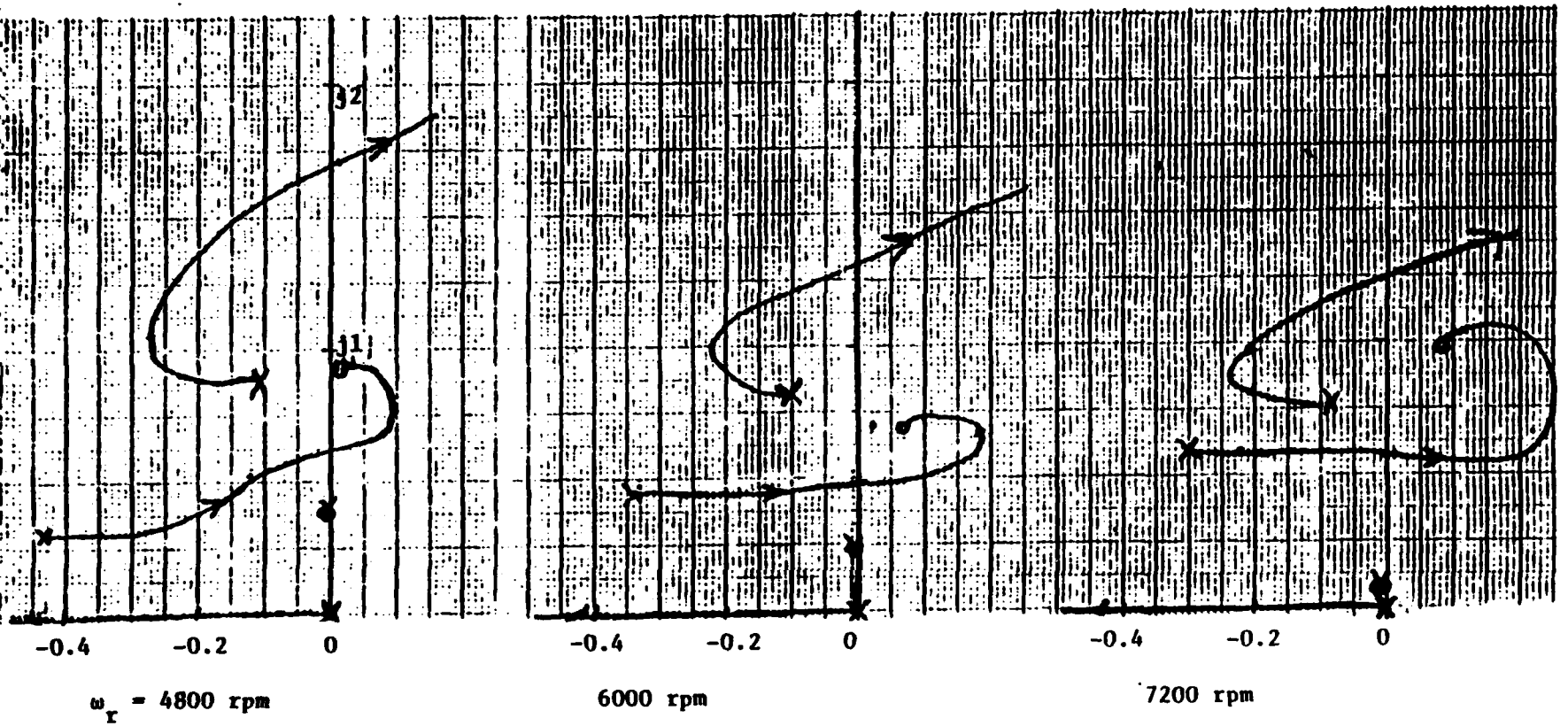


Figure 16. Closed loop pole movement with integrator gain. Rotor state feedback parameters $C_1 = 0.2$ and $C_2 = 2.5\omega_r$. Feedback of d and q axis capacitor currents with gain $C_3 = 0.6$.

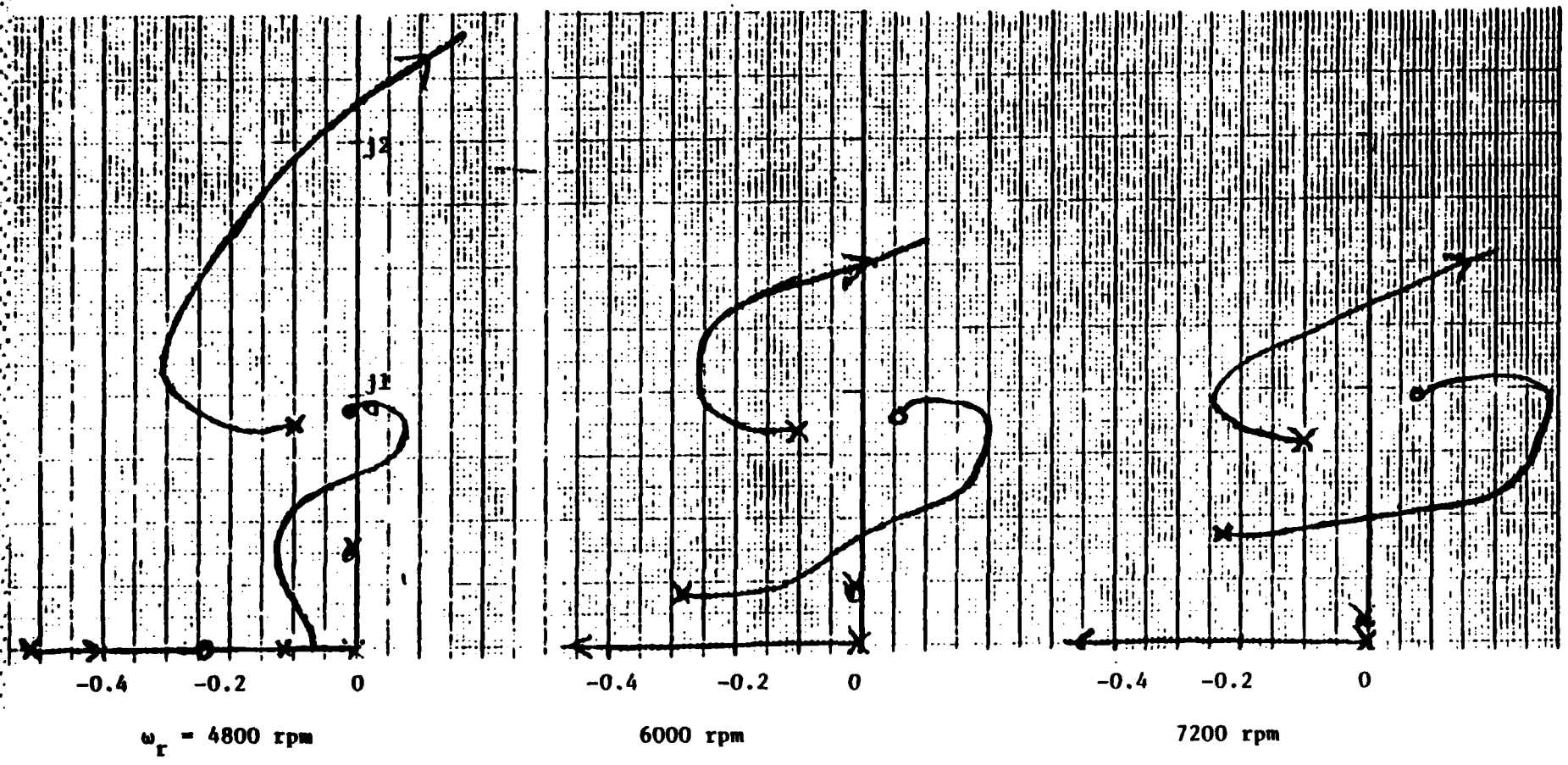
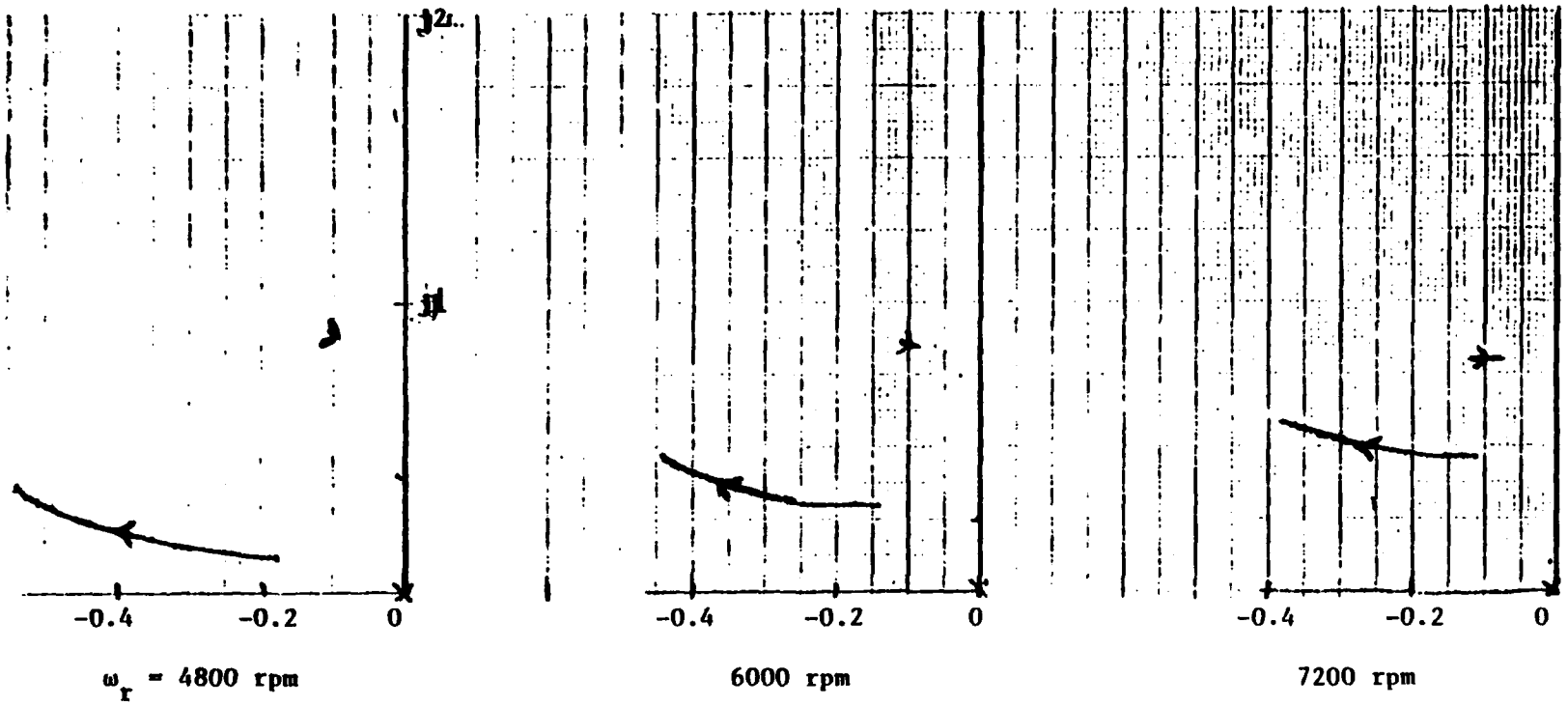


Figure 17. Closed loop pole movement with integrator gain. Rotor state feedback parameter C_1 = 0.2 and $C_2 = 2.5\omega_r$. Feedback of stator power with gain C_3 = 0.6.

TABLE 3

speed / eigenvalues	4800 rpm	6000 rpm	7200 rpm
	-.40	-.29	-.14
	-.10 ± j.19	-.12 ± j.25	-.13 ± j.44
	-.11 ± j.89	-.12 ± j.85	-.12 ± j.80



ω_r = 4800 rpm 6000 rpm 7200 rpm

Figure 18. Open loop system poles with variation of feedback of stator currents. Stator current feedback parameter C_3 varied from 0.0 to 0.9. Field current feedback parameter $C_1 = 0.6$, $C_2 = 2.5\omega_r$.

Conclusions

This project considers two aspects of the control of cascaded doubly fed machine (CDFM) generator systems. In the first step, the controllability of the system in the supersynchronous operating mode was considered. The results show that the supersynchronous mode exhibits similar characteristics to the subsynchronous mode, which was considered during an earlier project. The supersynchronous mode exhibits certain characteristics which could be undersirable in systems requiring larger speed ranges then have been considered here.

The second step of the research considered the effect of shunt capacitance connected at the generator output, with permanently connected capacitors. The results show that stability and good response can be provided with field current feedback except at light load conditions. At light loads, stability and good response can be attained by including feedback of a generator output quantity. Of the options examined, feedback of the output power would appear to be the most easily implemented system. The results of this step show that permanently connected capacitors should be considered as a source of excitation for a CDFM generator system.

References

1. T.H. Ortmeyer and W.U. Borger, "Brushless Generation with Cascaded Doubly Fed Machines," Proceedings of the IEEE 1983 National Aerospace and Electronics Conference, Dayton, Ohio, pp. 1420-1425.

2. T.H. Ortmeyer, "Negative Frequency Aspects of Doubly Fed Machine Analysis," Proc. IEEE Vol. 71, No. 8, August, 1983, p. 1017.

3. T.H. Ortmeyer and W.U. Borger, "Control of Cascaded Doubly Fed Machines for Generator Applications," IEEE Trans. Vol. PAS-103, No. 9, September, 1984, pp. 2564-2571.

4. J.A. Weimer and T.H. Ortmeyer, "Experimental Cascaded Doubly Fed Variable Speed Constant Frequency Generator System," Proceedings of the IEEE 1984 National Aerospace and Electronics Conference, Dayton, Ohio, pp. 444-451.

5. T.H. Ortmeyer and J.A. Weimer, "Implementation of CDFM Generator Control," Submitted to IEEE Power Engineering Society.

6. A.E. Fitzgerald and C. Kingsley, Jr. Electric Machinery, 2nd edition, 1961. New York: McGraw Hill.

Appendix 1

Per Unit System

The per unit system used is:

Base current = machine rated rms phase current

Base Voltage = machine rated rms volts

Base power = machine rated volt-amps

Base Frequency = machine rated output frequency

The other bases follow from these definitions. The analysis and simulations were conducted on the output machine base. The base of the s-plane operator is 2π x frequency base.

Appendix 2

Analysis and Simulation Program Listings

Step 1

```
FORTRAN IV G1  RELEASE 2.0                MAIN                DATE = TUE DEC 06, 1983

0001                  IMPLICIT REAL*8 (A-H,L,O-Z)
0002                  COMPLEX*16 ALFA(7),WK(7),Z(7)
0003                  DIMENSION A(7,7),B(7,7),RTA(7)
0004                  READ (5,106) RS, RR, LS, LR, LM, P1
0005                  READ (5,100) RA, RF, LA, LF, LAM, P2
0006                  READ (5,110) FO, SPMIN, SPMAX, DELTS, FBASE
0007              100 FORMAT (6F10.4)
0008                  WRITE (6,111) RS, RR, LS, LR, LM, P1
0009                  WRITE (6,120) RA, RF, LA, LF, LAM, P2
0010                  WRITE (6,130) FO, SPMIN, SPMAX, DELTS, FBASE
0011              110 FORMAT (11X,'RS=',G10.4,'RR=',G10.4,'LS=',G10.4,
                     # 5X,'LR=',G10.4,'LM=',G10.4,5X,'P1=',G10.4)
0012              120 FORMAT (11X,'RA=',G10.4,5X,'RF=',G10.4,5X,'LA=',G10.4,
                     # 5X,'LF=',G10.4,5X,'RF=',G10.4,5X,'LA=',G10.4)
0013              130 FORMAT (11X,'FO=',G10.4,5X,'SHAFT SPEED=',F10.1,1X,'RPM=',
                     # 'MIN',F10.1,1X,'MAX WITH',F4.1,2X,'INCREMENTS',1X,'FBASE=',
                     # G7.2)
0014                  READ (5,100) VO,IO,PHI,G1
0015                  WRITE (6,131) VO,IO,PHI,G1
0016              131 FORMAT(' VO=', G10.4,' IO=',G10.4,' PHI=', G10.4,' G1=',G10.4)
0017                  READ (5,100) C1,C2
0018                  WRITE (6,141) C1,C2
0019              141 FORMAT (10X,'C1=',G10.4,2X,'C2=',G10.4)
0020                  KNT =0
0021                  CON = 1.0
0022                  GST = G1
0023                  N=7
0024                  WBASE = 6.283*FBASE
0025                  SHAFT = SPMIN
0026                  WEO = FO / FBASE
0027                  DSP = (SPMAX-SPMIN)/DELTS
0028              16  CONTINUE
0029                  G1 = GST
0030                  WRO = SHAFT*P1/(120.0*FBASE)
0031                  WSO = (WEO - WRO)
0032                  IF(WSO.LT.0.) CON = -1.0
0033                  WE2O = CON * WSO
0034                  WS2O = WE2O - (P2/P1)*WRO
0035                  IXS = -10*DCOS(PHI)
0036                  IYS = 10*DSIN(PHI)
0037                  ZL = VO/IO
0038                  RL = ZL*DCOS(PHI)
0039                  LL = ZL*DSIN(PHI)/WEO
0040                  DO 15 KL=1,19
0041                  DO 10 K=1,N
0042                  DO 11 J=1,N
0043                  A(K,J) = 0.
0044                  B(K,J) = 0.
0045              11  CONTINUE
0046              10  CONTINUE
0047                  A(1,1) = LS*LL
0048                  A(2,2) = LS*LL
0049                  A(3,3) = LR*LA
0050                  A(4,4) = LR*LA
```

```
0051                    A(2,5)=LF
0052                    A(5,6)=LF
0053                    A(1,3) = LM
0054                    A(2,4) = LM
0055                    A(4,1)=LA
0056                    A(4,2) = LM
0057                    A(3,5) = -LAM
0058                    A(4,5) = -LAM*CON
0059                    A(5,3) = -LAM
0060                    A(6,4) = -LAM*CON
0061                    A(1,1) = RS+RL
0062                    A(1,2) = -WE0*(LS+LL)
0063                    A(1,4) = -WE0*LM
0064                    A(2,1) = WE0*(LS+LL)
0065                    A(2,2) = RS+RL
0066                    A(2,3) = WE0*LM
0067                    A(3,2) = -WS0*LM
0068                    A(3,3) = RR+RA
0069                    A(3,4) = -(WS0*LR+WE20*LA*CON)
0070                    A(3,5) = WE20*LAM
0071                    A(4,1) = WS0*LM
0072                    A(4,3) = WS0*LR+WE20*LA*CON
0073                    A(4,4) = RR+RA
0074                    A(4,5) = -WE20*LAM*CON
0075                    A(5,4) = WS20*LAM*CON
0076                    A(5,5)=RF+C1
0077                    A(5,6)= -WS20*LF -C2
0078                    A(6,6)=RF+C1
0079                    A(6,5)=WS20*LF+C2
0080                    A(6,3) = -WS20*LAM
0081                    IYR = (V0-RS*IXS+WE0*LS*IYS)/(-WE0*LM)
0082                    IXR = (-RS*IYS - WE0*LS*IXS)/(WE0*LM)
0083                    IXF = (-WS0*LM*IXS-(WS0*LR+CON*WE20*LA)*IXR-(RR+RA)*IYR)/
                      *   (-WE20*LAM*CON)
0084                    IYF=(-(RR+RA)*IXR+WS0*LM*IYS+(WS0*LR+CON*WE20*LA)*IYR)/(WE20*LAM)
0085                    VXF = (RF+C1)*IXF+CON*WS20*LAM*IYR-(WS20*LF+C2)*IYF
0086                    VYF =(RF+C1)*IYF-WS20*LAM*IXR+(WS20*LF+C2)*IXF
0087                    VDF = DSQRT(VXF*VXF+VYF*VYF)
0088                    DSR = VXF/VDF
0089                    DSR=-(VYF/VDF)*CON
0090                    A(7,1) = RS*DSR + WE0*LS*DSR
0091                    A(7,2) = RS*DSR - WE0*LS*DSR
0092                    A(7,3) = WE0*LM*DSR
0093                    A(7,4) = -WE0*LM*DSR
0094                    A(7,1) = LS*DSR
0095                    A(7,2) = LS*DSR
0096                    A(7,3) = LM*DSR
0097                    A(7,4) = LM*DSR
0098                    B(7,7) = WBASE
0099                    A(5,7) =-G1
0100                    DO 13 J=1,N
0101                    DO 13 K=1,N
0102                 13 A(J,K) = -A(J,K)
0103                    WRITE(6,140) G1,WPO
```

```
0104                    IF (DABS(A(20)).LT.0.1D-4) GOTO 80
0105                    CALL EIGZF(A,N,M,N,0,KND,ALFA,BETA,Z,N,WK,KER)
0106                    IF(KER.GT.128) GOTO 50
0107                140 FORMAT (20X,G12.4,10X,G10.4)
0108                    DO 12 J=1,M
0109                    ALFA(J) = ALFA(J) / BETA(J)
0110                12  WRITE(6,160) ALFA(J)
0111                160 FORMAT (40X,2(10X,G12.5))
0112                    GOTO 81
0113                80  CONTINUE
0114                    DO 82 JPR=1,7
0115                    A(JPR,6)=A(JPR,7)
0116                82  A(JPR,6)=A(JPR,7)
0117                    DO 83 JPR=1,6
0118                    A(6,JPR)=A(7,JPR)
0119                83  A(6,JPR) = A(7,JPR)
0120                    CALL EIGZF(A,B,1,N,0,-1,KND,ALFA,BETA,Z,N,WK,KER)
0121                    IF (KER.GT.128) GOTO 50
0122                    NM=J-1
0123                    DO 14 J=1,NM
0124                    ALFA(J)=ALFA(J)/BETA(J)
0125                14  WRITE (6,160) ALFA(J)
0126                81  CONTINUE
0127                    G1 = G1 * 4.0
0128                15  CONTINUE
0129                    IF(SHAFT.GT.SPMAX) GOTO 17
0130                    SHAFT = SHAFT + DSP
0131                    GOTO 16
0132                17  CONTINUE
0133                    STOP
0134                50  WRITE(6,150) KER
0135                150 FORMAT (10X,I4)
0136                    STOP
0137                    END

 *OPTIONS IN EFFECT*  NOTERM,ID,ERRDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP,NOTEST
 *OPTIONS IN EFFECT*  NAME = MAIN     , LINECNT =      56
 *STATISTICS*     SOURCE STATEMENTS =      137,PROGRAM SIZE = 001402
 *STATISTICS*  NO DIAGNOSTICS GENERATED
/DATA                                                                    3.85
00CF90 BYTES USED
EXECUTION BEGINS
        RS= .20000-01RR= .25000-01LS= 4.080        LR= 4.080   LM= 4.000        PI= 6.000
        KA= .80000-02     ZF=  10000-01     LA= 4.040
```

```
0001                  IMPLICIT REAL*8 (A-H,L,1,O-Z)
0002                  DIMENSION Y(7),W(7,9),C(24)
0003                  EXTERNAL FCN
0004                  COMMON /AL/FT,XT,XM,VDF,RR,XR,SLIP,VQF,LS,LM,CRD
0005                  COMMON/AL4/ B10,B20,B30,B120,B130,B230,B1Q,B2Q,B3Q,B12Q,B13Q,B23Q
0006                  COMMON /AL3/ N
0007                  COMMON /AL2/
     C RS,RS,XX),VOST,G1,G2,VQ,LT,LR ,PHII
0008                  COMMON/AL1/RA,LA,RF,LF,LAM,P2,WS,WE2,WS2,WE,CON
0009                  READ(5,100)TDELT,TFINAL
0010                  WRITE(6,150)TDELT,TFINAL
0011            150   FORMAT('TIME INCREMENT=',F7.4,2X,'FINAL TIME =',F7.4)
0012                  READ (5,100) RS,RR,LS,LR,LM,P1
0013                  READ (5,100) RA,RF,LA,LF,LAM,P2
0014                  READ (5,100) VQ,PQ,QQ,FQ,SHAFT
0015                  WRITE (6,110) RS,RR,LS,LR,LM,P1
0016                  WRITE (6,121) RA,RF,LA,LF,LAM,P2
0017            121   FORMAT(' ',10X,'RA',F10.4,5X,'RF=',F10.4,5X,'LA=',F10.4,
     C5X,'LF=',F10.4,5X,'LAM=',F10.4,5X,'P2=',F10.2)
0018                  WRITE (6,120)VQ,PQ,QQ,FQ,SHAFT
0019            100   FORMAT (6F10.4)
0020            110   FORMAT('1RS=',F8.4,4X,'RR=',F8.4,4X,'LS=',F8.4,4X,
     C'LR=',F8.4,4X,'LM=',F8.4,4X,'POLES =',F8.4)
0021            120   FORMAT(' INITIAAL CONDITIONS OUTPUT: VQ=',F7.3,4X,'PQ=',
     CF7.4,2X,'QQ=',F7.3/20X,'FQ=',F7.2,'SHAFT SPEED=',F10.2,
     C'RPM')
0022                  READ(5,100)DELV,DELN,DELP,DELX,G1,G2
0023                  WRITE(6,130)DELV,DELN,DELR,DELX,G1,G2
0024            130   FORMAT('STEP CHANGES:VOLTAGES=',F7.3,2X,'SHAFT SPEED =',
     CF7.3,2X,'LOAD RESISTANCE',F7.3,2X,'LOAD REACTANCE',F7.3,
     C'GAIN G1 = ',F7.3,5X,'G2=',F7.3)
0025                  READ (5,101)K
0026            101   FORMAT (I1)
0027                  WRITE (6,140)K
0028            140   FORMAT('0K=',I3,4X,'(K=1 FOR PER UNIT OPERATION,',
     C'K = 2 FOR DIMENSIONAL OPERATION')
                C     CALCULATE GENERATOR CONSTANTS
0029                  CONST = 0.0
0030                  N4 = 7
0031                  TOL = 0.00001
0032                  PAI = 3.14159
0033                  CO1 = 1.0
0034                  WO = 2.*PAI*FQ
0035                  WOB = WO
0036                  CRD = 180./PAI
0037                  IF(K.EQ.1) WO= 1.
0038                  IF(K.EQ.2) WOB = 1.
0039                  XM = WO*LM
0040                  XS = WO*LS
0041                  XR = WO*LR
0042                    = 0
0043                  T = -2.*TDELT
0044                  VOST = VQ
0045                  KQQ = 1
```

```
                C       CALCULATE INITIAL CONDITIONS
0046                    WSO = SHAFT*PI/120.
0047                    SPE = F0*120./PI
0048                    SLIP = (SPE-SHAFT)/SPE
0049                    IX = -P0/V0
0050                    IY = Q0/V0
0051                    IOSQ = IX*IX+IY*IY
0052                    IF(IOSQ.LT.0.001)N = 1
0053                    WE = W0
0054                    WS = SLIP*W0
0055                    IF (WS.LT.0.0) CON=-1.0
0056                    WE2 = CON*SLIP*W0
0057                    WS2 = WE2-(P2/P1)*(WE-WS)
0058                    IXS = IX
0059                    WE0 = WE
0060                    WE20 = WE2
0061                    WS20 = WS2
0062                    WS0 = WS
0063                    IYS = IY
0064                    IYR = (V0-RS*IXS+WE0*LS*IYS)/(-WE0*LM)
0065                    IXR = (-RS*IYS-WE0*LS*IXS)/(WE0*LM)
0066                    IXF = (-WS0*LM*IXS-(WS0*LR+CON*WE20*LA    )*IXR-(RR+RA)*IYR)/
                      C (-WE20*LAM*CON)
0067                    IYF = (-(RR+RA)*IXR+WS0*LM*IYS+(WS0*LR+CON*WE20*LA)*IYR)
                      C/(WE20*LAM)
0068                    VXF = RF*IXF+CON*WS20*LAM*IYR-WS20*LF*IYF
0069                    VYF = RF*IYF-WS20*LAM*IXR+WS20*LF*IXF
0070                    VDF =DSQRT(VXF*VXF+VYF*VYF)
0071                    VQF = 0.
0072                    A=VXF/VDF
0073                    B=VYF/VDF
0074                    Y(2) = IXR*A+IYR*B*CON
0075                    Y(5) = -IXR*B*CON+IYR*A
0076                    Y(1) = IX*A+IY*B*CON
0077                    Y(4) = -IX*B*CON+IY*A
0078                    Y(3) = IXF*A+IYF*B
0079                    Y(6) = -B*IXF+A*IYF
0080                    Y(7) = VDF
0081                    WRITE (6,*) Y(1),Y(2),Y(3),Y(4),Y(5),Y(6),Y(7)
0082                    WRITE (6,110)IYR,IXR,IYF,IXF,VYF,VXF
0083                    BD=(LS*(LR+LA)*LF-LAM*LAM*LS-LM*LM*LF)/W0B
0084                    B11D=((LR+LA)*LF-LAM*LAM)/BD
0085                    B21D = LS*LF/BD
0086                    B31D=(LS*(LR+LA)-LM*LM)/BD
0087                    B12D = (-LM*LF)/BD
0088                    B13D = (-LM*LAM)/BD
0089                    B23D = LS*LAM/BD
0090                    B11=B11D
0091                    B21=B21D
0092                    B31=B31D
0093                    B12D=B12D
0094                    B13D=CON*B13D
0095                    B23D=CON*B23D
0096                    IF(N.EQ.0) GO TO 40
```

```
0097                    B2P = B2
0098                    B4P = B4
0099                    B2 = 0.
0100                    B4 = WO*WO/LR
0101                    RT = RS
0102                    XT = XS
0103                    GO TO 50
0104              40    R = RO/IOSO
0105                    X = XO/IOSO
0106                    RT = RS*R
0107                    XT = XS*X
0108              50    CONTINUE
0109                    LT = XT/WO
0110                    WRITE (5,102)
0111              102   FORMAT (                '1',4X, 'TIME',7X, 'OUTPUT',6X,
                 C 'OUTPUT',6X, 'ANGLE',
                 C5X, 'ANGLE',  9X, 'IQS', 9X, 'IDR', 9X, 'IQS', 9X, 'IQR',
                 C 3X, 'VDR',  9X, 'VQR'  /
                 C16X, 'VOLTAGE', 5X, 'CURRENT', 3X, 'VOUT TO VDR', 1X,
                 C'IO TO VO')
0112                    CALL WRIT (T,Y,K4)
0113              20    TEND = T+TDELT
0114                    CALL OVERK(K4,FCN,T,Y,TEND,TOL,KND,C,K4,W,KER)
0115                    IF(KND.LT.0) GO TO 15
0116                    IF(KER.GT.0) GO TO 15
0117                    CALL WRIT (T,Y,K4)
0118                    IF(TEND.LT.-.00005) GO TO 20
                C       INPUT CONDITIONS
0119                    VOST = VOST + DELV
0120                    SHAFT = SHAFT + DELN
0121                    SLIP = (SPE-SHAFT)/SPE
0122                    WS = SLIP
0123                    WE2 = CON*SLIP*WO
0124                    WS2 = WE2-(P2/P1)*(WE-WS)
0125                    IF(DELR.GT.0.001.OR.DELX.GT.0.001) GO TO 60
0126                    GO TO 61
0127              60    IF (N.EQ.0) GO TO 61
0128                    N = 0
0129                    B2 = B2P
0130                    B4 = B4P
0131              61    CONTINUE
0132                    RT = RT + DELR
0133                    XT = XT + DELX
0134              25    TEND = T + TDELT
0135                    NN = NN+1
0136                    CALL OVERK(K4,FCN,T,Y,TEND,TOL,KND,C, K4,W,KER)
0137                    IF(KND.LT.0) GO TO 15
0138                    IF(KER.GT.0) GO TO 15
0139                    CALL WRIT (T,Y,K4)
0140                    IF (TEND.LT.TFINAL) GO TO 25
0141                    STOP
0142              15    WRITE (6,160) KND,KER
0143              160   FORMAT('ERROR-KND=',I2,'KER=',I2)
0144                    STOP
```

```
0001                  SUBROUTINE FCN(K4,TD,Y,YPRIME)
0002                  IMPLICIT REAL*8 (A-H,L,I,O-Z)
0003                  DIMENSION Y(K4),YPRIME(K4)
0004                  COMMON /AL/RT,XT,AM,VDF,RR,AR,SLIP,VOF,LS,LM,CRD
0005                  COMMON/BL3/ O
0006                  COMMON /BL2/XS,WS
                     C,WS,VOST,G1,G2,V0,LT,LR,PHII
0007                  COMMON/BL4/B1D,B2D,B3D,B12D,B13D,B23D,B1Q,B2Q,B3Q,B12Q,B13Q,B23Q
0008                  COMMON/BL1/RA,LA,RF,LF,LAM,P2,WS,WE2,WS2,WE,CON
0009                  VDF = Y(7)
0010                  A = -RT*Y(1)+WE*(LT*Y(4)+LM*Y(5))
0011                  B = -(RR+RA)*Y(2)+(LR+LA)*Y(5)*WS+WS*LM*Y(4)-WE2*LAM*Y(6)
0012                  C = VDF-RF*Y(3)+WS2*(LF*Y(6)-LAM*Y(5)*CON)
0013                  D = -RT*Y(4)-WE*(LT*Y(1)+LM*Y(2))
0014                  E = -(RR+RA)*Y(5)-(LR+LA)*WS*Y(2)-LM*WS*Y(1)+WE2*LAM*Y(3)*CON
0015                  F = VOF-RF*Y(6)-WS2*(LF*Y(3)-LAM*Y(2))
0016                  IF(O.EQ.1) GO TO 30
0017                  YPRIME(1) = B1D*A+B12D*B+B13D*C
0018                  YPRIME(4) = B1Q*D+B12Q*E+B13Q*F
0019                  GO TO 40
0020               30 YPRIME(1) = 0.
0021                  YPRIME(4) = 0.
0022               40 CONTINUE
0023                  YPRIME(2) = B12Q*A+B2D*B+B23D*C
0024                  YPRIME(3) = B13Q*A+B23D*B+B3D*C
0025                  YPRIME(6) = B13Q*D+B23Q*E+B3Q*F
0026                  YPRIME(5) = B12Q*D+B2Q*E+B23Q*F
0027                  VDS = RS*Y(1)-XS*Y(4)-XM*Y(5)+(LS*YPRIME(1)+LM*YPRIME(2))/WOB
0028                  VQS = RS*Y(4)+XS*Y(1)+XM*Y(2)+(LS*YPRIME(4)+LM*YPRIME(5))/WOB
0029                  V0 =DSQRT(VDS*VDS+VQS*VQS)
0030                  YPRIME(7) = G1*(VOST-V0)
0031                  RETURN
0032                  END
```

```
*OPTIONS IN EFFECT*   NOTERM,ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP,NOTEST
*OPTIONS IN EFFECT*   NAME = FCN      , LINECNT =      56
*STATISTICS*     SOURCE STATEMENTS =      32,PROGRAM SIZE = 000648
*STATISTICS*   NO DIAGNOSTICS GENERATED
```

```
 FORTRAN IV G1  RELEASE 2.0                WRIT                    DATE = TUE DEC 06, 1983                    PAGE

    0001                      SUBROUTINE WRIT(T,Y,K4)
    0002                      IMPLICIT REAL*8 (A-H,L,O-Z)
    0003                      DIMENSION Y(K4)
    0004                      COMMON /BL/RT,AT,AM,VDF,PR,XM,SLIP,VQF,LS,LM,CRD
    0005                      COMMON /BL3/ H
    0006                      COMMON /BL2/
                             1AS,RS,WOR,VOST,G1,G2,VO,LT,LR,PHII
    0007                      IA =DSQRT(Y(1)*Y(1)+Y(4)*Y(4))
    0008                      IF(N.EQ.1) GO TO 10
    0009                      PHII =DATAN2(Y(4),Y(1))*CRD
    0010                      GO TO 11
    0011                10    PHII = 0.
    0012                11    CONTINUE
    0013                      WRITE(6,170) T,VO,IA,PHII,Y(1),Y(2),Y(3),Y(4),Y(5),Y(6),Y(7)
    0014                170   FORMAT(' ',3(F9.4,3X),2(F7.2,5X),6(F9.4,3X))
    0015                      RETURN
    0016                      END

     *OPTIONS IN EFFECT*   NOTERM,ID,ENCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP,NOTEST
     *OPTIONS IN EFFECT*   NAME = WRIT      , LINECNT =     56
     *STATISTICS*     SOURCE STATEMENTS =       16,PROGRAM SIZE = 000344
     *STATISTICS*   NO DIAGNOSTICS GENERATED

     *STATISTICS*   NO DIAGNOSTICS THIS STEP                                                    4.1S
/DATA
009870 BYTES USED
EXECUTION BEGINS
TIME INCREMENT= 0.0020  FINAL TIME = 0.7000
```

Analysis and Simulation Program Listings

Step 2

```
                                                                DATE = FRI MAY 25, 1984

      1                 IMPLICIT REAL*8 (A-H,L-Z)
      2                 COMPLEX*16 ALF(11),WK(11),Z(11)
      3                 DIMENSION A(11,11),B(11,11),BETA(11)
                        PROGRAM COMPUTES EIGENVALUES OF A CASCADED DOUBLE FED GENERATOR
                        WITH PASSIVE RL LOAD AND CAPACITIVE VAR GENERATION AT THE
                        GENERATOR OUTPUT TERMINAL.
                        INNER CONTROL LOOP- IDEAL STATE FEEDBACK OF FIELD CURRENTS
                        OUTER CONTROL LOOP- VOLTAGE REGULATOR AND FREQUENCY SUMMER
      4                 READ (5,100) RS, RF, LS, LF, LM, P1
      5                 READ (5,100) RA, RE, LA, LE, LAM, P2
      6                 READ (5,100) EC, SPMIN, SPMAX, DELTS, FBASE
      7           100   FORMAT (6G10.4)
      8                 WRITE (6,110) RS, RF, LS, LF, LM, P1
      9                 WRITE (6,120) RA, RE, LA, LE, LAM, P2
     10                 WRITE (6,130) EC, SPMIN, SPMAX, DELTS, FBASE
     11           110   FORMAT (11X,'RS=',G10.4,'RF=',G10.4,'LS=',G10.4,
                       * 'LA=',G10.4,'LE=',G10.4,'LM=',G10.4,5X,'P1=',G10.4)
     12           120   FORMAT (11X,'RA=',G10.4,5X,'RE=',G10.4,5X,'LA=',G10.4,
                       * 5X,'LE=',G10.4,5X,'LAM=',G10.4,5X,'P2=',G10.4)
     13           130   FORMAT (11X,'EC=',G10.4,5X,'SHAFT SPEED=',F10.1,1X,'RPM=',
                       * 'MIN',F10.1,1X,'MAX,WITH',F4.1,2X,'INCREMENTS',1X,'FBASE=',
                       * G7.2)
     14                 READ (5,100) VO,IO,PHI,G1,QCOMP
     15                 WRITE (6,131) VO,IO,PHI,G1,QCOMP
     16           131   FORMAT(' LOAD VALUES, VO=', G10.4,' IO=',G10.4,' PHI=', G10.4,
                       * ' G1=',G10.4,' QCOMP=',G10.4)
     17                 READ (5,100) C1,C2
     18                 WRITE (6,141) C1,C2
     19           141   FORMAT (10X,'C 11=',G10.4,2X,'C2=',G10.4)
     20                 KMD =0
                          CON=1.0  FOR ASYNCHRONOUS OPERATION
                          G1 IS VOLTAGE REGULATOR GAIN
                          DSP IS SPEED INCREMENT
                          MINIMUM VALUE OF LOAD INDUCTANCE REQUIRED FOR SOLUTION
     21                 IF (PHI.LT.5.0D) PHI=5.0D
     22                 PHI = PHI/57.29578
     23                 CON = 1.0D
     24                 DSP = 1.0
     25                 N=11
     26                 FBASE = 0.5D0*FBASE
     27                 SPMIN = SPMIN
     28                 SPMAX = SPMAX / FBASE
     29                 DELTS = DELTS/FBASE
     30                 QCOMP=QCOMP/VO
     31                 VO=1.0D0/(EC*FBASE)
     32                 NSTP = (SPMAX-SPMIN)/DELTS
     33           10    CONTINUE
     34                 S1 = SPMIN
     35                 W1 = S1*LE*P1/(120.0*FBASE)
     36                 W2 = (W1 - W1)
     37                 IF(S1.LT.0.) W1N = -1.0D0
     38                 W1 = W1 * W1N
     39                 W2 = W2 - (P2/P1)*W1
     40                 IXL = -IO*DCOS(PHI)
```

```
      [illegible](PHI)
      [illegible] = V [illegible]
      [illegible]
      [illegible]
      [illegible] (PHI)
      [illegible] = [illegible]SIN(PHI)/W[illegible]
      [illegible] (6,1??) [illegible],CAP
1?? FORMAT (10X'[illegible] VALUES', [illegible]=',G10.4,' LL=',G10.4
     *,' [illegible]=',G10.4,' [illegible]=',G10.4,' ICAP=',G10.4,' CAP=',G10.4)
      [illegible] 1 [illegible]=1,19
      [illegible] 1[illegible] K=1,[illegible]
      [illegible] 11 J=1,[illegible]
      [illegible](K,J) = [illegible].
      [illegible](K,J) = [illegible].
   11 CONTINUE
   1[illegible] CONTINUE
      [illegible](1,1) = LS
      [illegible] = L[illegible]
      [illegible] = L[illegible]+L[illegible]
      [illegible] = L[illegible]+L[illegible]
      [illegible]=LF
      [illegible]=LF
      [illegible](1,[illegible]) = LM
      [illegible](2,4) = LM
      [illegible](3,1)=LM
      [illegible](4,[illegible]) = LM
      [illegible] = -LAM
      [illegible] = -LAM*CON
      [illegible] = -LAM
      [illegible] = -LAM*CON
      [illegible] =CAP
      [illegible]=CAP
      [illegible](10,10)=LL
      [illegible](11,11)=LL
      [illegible](1,1) = RS
      [illegible](1,2) = -W[illegible]*LS
      [illegible](1,4) = -W[illegible]*LM
      [illegible](1,[illegible])=-1.[illegible]
      [illegible](2,1) = W[illegible]*LS
      [illegible] = R[illegible]
      [illegible] = W[illegible]*LM
      [illegible]=-1.[illegible]
      [illegible] = -W[illegible]*LM
      [illegible] = RR+RA
      [illegible] = -(W[illegible]*LR+W[illegible]*LA*CON)
      [illegible] = W[illegible]*L[illegible]
      [illegible](4,1) = WS[illegible]*LM
      [illegible] = W[illegible]*LR+W[illegible]*LA*CON
      [illegible] = RR+RA
      [illegible] = -W[illegible]*LAM*CON
      [illegible] = W[illegible]*LAM*CON
      [illegible]=RF+C1
      [illegible]= -W[illegible]*LF-C2
      [illegible]=RF+C1
```

```
                      A(3,1) = WS20*LF+C2
                      A(3,2) = -WS20*LAM
                      A(4,1)=1.00
                      A(4,10)=-1.00
                      A(5,4)=-WE0*CAP
                      A(5,2)=1.00
                      A(5,11)=-1.00
                      A(6,3)=WE0*CAP
                      A(6,1)=0.0
                      A(10,10)=-WE0*LL
                      A(10,8)=1.00
                      A(11,11)=WE0*LL
                      A(11,10)=WE0*LL
                      A(11,9)=1.00
                      IYS = (VF-DS*TAU+WE0*LS*IYS)/(-WE0*LM)
                      IXS = (-RS*IYS - WE0*LS*IXS)/(WE0*LM)
                      IXF = (-WS0*LM*IAS-(WS0*LR+CON*WE20*LA)*IXR-(RR+RA)*IYR)/
                     +  (-WE0*LAM*CON)
                      IYF=(-(RF+RA)*IXR+WS0*LM*IYS+(WS0*LR+CON*WE20*LA)*IYR)/(WE20*LAM)
                      VXF = (RF+C1)*IXF+CON*WS20*LAM*IYR-(WS20*LF+C2)*IYF
                      VYF =(RF+C1)*IYF-WS20*LAM*IXR+(WS20*LF+C2)*IXF
                      VDF = DSQRT(VXF*VXF+VYF*VYF)
                      DSR = VXF/VDF
                      QSR=-(VYF/VDF)*CON
C                     A(7,1) = RS*DSR + WE0*LS*QSR
C                      A(7,2) = RS*QSR - WE0*LS*DSR
C                     A(7,3) = WE0*LM*QSR
                      A(7,4) = -WE0*LM*DSR
                      A(7,1) = LS*DSR
                      A(7,2) = LS*QSR
                      A(7,3) = LM*DSR
                      A(7,4) = LM*QSR
                      A(7,9)=DSR
                      A(7,8)=QSR
                      A(7,7)= WBASE
                      A(5,7) =-G1
                      DO 1 JKL=1,11
                    1 WRITE (6,*) (A(JKL,KKL),B(JKL,KKL),KKL=1,11)
                      DO 15 J=1,N
                      DO 15 K=1,J
                    1 A(J,K) = -A(J,K)
                      WRITE(6,140)
                      IF (DABS(WBASE).LT.0.1D-4) GOTO 99
                      CALL DGEIGZ(A,N,NMAX,ALFA,BETA,Z,N,WK,KER)
                      IF(KER.GT.128) GOTO 99
                    1 FORMAT(' ',3X,'ALFA',13X,'BETA',13X,'LAMBDA')
                      DO 1 J=1,N
                      ALFA(J) = ALFA(J) / BETA(J)
                      WRITE(6,2) ALFA(J)
                    2 FORMAT(' ',1P,E16.8)
                      STOP
                      END
                      SUBROUTINE DGEIGZ(A,N,NMAX,ALFA,BETA,Z,N,WK,KER)
                      IMPLICIT REAL*8 (A-H,O-Z)
                      DIMENSION A(1),ALFA(1),BETA(1),Z(1),WK(1)
                      KER=0
                      IF(N-1)1,2,3
```

```
FORTRAN IV G1  RELEASE 2.0                    MAIN                    DATE = 82141 MAY 22, 1984                    PAGE 3

0136                        DO 6 J=1,N
0137                        A(J,KP1)=B(J,KP1)
0138                    6   A(J,KP1)=B(J,KP1)
0139                        KP1=K-1
0140                        DO 65 K=1,KM
0141                        KP1=K+1
0142                        DO 65 J=1,KM
0143                        A(KP1,J)=B(KP1,J)
0144                   65   B(2,J)=B(7,J)
0145                        CALL FIDGE(A,1,7,N-1,KMD,ALFA,BETA,Z,N,K,KBB)
0146                        IF (KBB.GT.10) GOTO 50
0147                        KM=N-1
0148                        DO 1 J=1,N
0149                        ALFA(J)=ALFA(J)/BETA(J)
0150                   10   WRITE (6,100) ALFA(J)
0151                   81   CONTINUE
0152                        J1 = 81 * 4.3
0153                   15   CONTINUE
0154                        IF(SHEET.GT.SMAX) GOTO 17
0155                        SHEET = SHEET + DSP
0156                        GOTO 15
0157                   17   CONTINUE
0158                        STOP
0159                   50   WRITE(6,150) KBB
0160                  150   FORMAT (10X,I4)
0161                        STOP
0162                        END

 *OPTIONS IN EFFECT*   NOTERM,ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP,NOTEST
```

```
0001                  [illegible]
0002                  [illegible]
0003                  [illegible]
                      [illegible] SERIES RL LOAD (SPECIFIED
                      [illegible] OF THE STATOR
                      [illegible] INCLUDES IDEAL RESISTANCE
                      [illegible] WITH GAIN G1.
0004                  [illegible]
0005                  [illegible]
0006                  [illegible]
0007                  [illegible]
0008                  [illegible]
0009                  [illegible]
0010                  [illegible]
0011            150   [illegible] TIME =',F7.4)
0012                  [illegible]
0013                  [illegible]
0014                  [illegible]
0015                  [illegible]
0016                  [illegible]
0017            121   [illegible]
0018                  [illegible]
0019            140   [illegible]
0020            111   [illegible]
0021            120   [illegible] INITIAAL CONDITIONS OUTPUT: VO=',F7.3,4X,'PO=',
                      CF7.3,2A,'DO=',F7.3/20X,'FO=',F7.2,'SHAFT SPEED=',F10.2,
                      C',',' OPERATION DCOMP=',F10.2)
0022                  [illegible]
0023                  [illegible]
0024            130   [illegible] CHANGES:VOLTAGES=',F7.3,2A,'SHAFT SPEED =',
                      CF7.3,2A,'LOAD RESISTANCE',F7.3,2A,'LOAD REACTANCE',F7.3,
                      C'G1 = ',F7.3)
0025                  [illegible]
0026            101   [illegible]
0027                  [illegible]
0028            14    [illegible]
                      [illegible]
                      [illegible]
                      [illegible]
0029                  [illegible]
0030                  [illegible]
0031                  [illegible]
0032                  [illegible]
0033                  [illegible]
0034                  [illegible]
0035                  [illegible]
0036                  [illegible]
0037                  [illegible]
0038                  [illegible]
0039                  [illegible]
0040                  [illegible]
```

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0065
0066
0067
0068                    IY=ICAP
0069                    IY=(VO-WS*IAS+WEO*LS*IYS)/(-WEO*LM)
0070                    IXS=(-WS*IYS-WEO*LS*IXS)/(WEO*LM)
0071                    IXR=(-WSO*LR**IXS-(WSO*LR+CON*WE20*LA    )*IXR-(RR+RA)*IYR)/
                       1(-WE20*LA*(RR+RA))
0072                    IYF=(-(RF+RA)*IXR+WSO*LR*IYS+(WSO*LR+CON*WE20*LA)*IYR)
                       2/(RF+RA)
0073                    IAS=IS
0074                    IXF=(RF+RA)*IXR+CON*WS20*LA*IYR-(WS20*LF+C2)*IYF
0075                    IYF=(RF+RA)*IYR-WS20*LA*IXR+(WS20*LF+C2)*IXF+C3*ICAP
0076                    VYF=1/(V**2*XF+VYF*VYF)
0077
0078
0079
0080
0081
0082
0083
0084
0085
0086
0087
0088
0089
0090
0091                    WRITE(6,*) (Y(I),I=1,N4)
```

```
0092                        [illegible]
0093                        [illegible]
0094                        [illegible]
0095                        [illegible]
0096                        [illegible]
0097                        [illegible]
0098                        [illegible]
0099                        [illegible]
0100                        [illegible]
0101                        [illegible]
0102                        [illegible]
0103                        [illegible]
0104                        [illegible]
0105                        [illegible]
0106                        [illegible]
0107                        [illegible]
0108                        [illegible]
0109                        [illegible]
0110                        [illegible]
0111                        [illegible]
0112                   40   [illegible]
0113                        [illegible]
0114                   50   [illegible]
0115                        [illegible]
0116                        [illegible]
0117                        [illegible]
0118                   10   [illegible]                    '1',4X, 'FREQ',7X, 'OUTPUT',6X,
                     C 'ANGLE',
                     C4X, 'ANGLE',  2X, 'IDS', 9X, 'IDR', 9X, 'IQS', 9X, 'IQR',
                     C4X, 'VDR',  4X, 'VQR'  /
                     C10X, 'VOLTAGE', 5X, 'CURRENT', 3X, 'VOUT TO VDR', 1X,
                     C'IN T) VQ')
0119                      CALL [illegible]
0120                   20 IF[illegible] = T-TOLT
0121                      CALL DVERK(X,F,[illegible],T,TEND,TOL,KIND,C,K4,W,KER)
0122                      IF(KER.LT.0) GO TO 15
0123                      IF(KER.GT.0) GO TO 15
0124                      [illegible]
0125                      IF [illegible] GO TO 20
0126                      [illegible]
0127                      [illegible]
0128                      [illegible]
0129                      [illegible]
0130                      [illegible]
0131                      [illegible]
0132                      [illegible]
0133                      [illegible]
0134                      [illegible]
0135                      IF[illegible].GE.0.001[illegible]EXA.(T.0.001)  GO TO 60
0136                      [illegible]
0137                   60 IF [illegible] GO TO 61
0138                      [illegible]
0139                      [illegible]
```

```
0140                                  [illegible]
0141                            [illegible]
0142                                  [illegible]
0143                                  [illegible]
0144                                  [illegible]
0145                            [illegible]
0146                                  [illegible]
0147                                  [illegible]
0148                                  [illegible]
0149                                  [illegible]
0150                                  [illegible]
0151                                  [illegible]
0152                                  [illegible]
0153                                  [illegible]
0154                                  [illegible]
0155                                  [illegible]
0156                            [illegible]
0157                            [illegible]
0158                                  [illegible]
0159                                  [illegible]
```

```
*OPTIONS IN EFFECT*   [illegible]
*OPTIONS IN EFFECT*   [illegible]
*STATISTICS*     [illegible]
*STATISTICS*   [illegible]
```

```
0001                          [illegible]
0002                          [illegible]
0003                          [illegible]
0004                          [illegible]VUF,VS,LS,LM,CRD
0005                          [illegible]
0006                          [illegible]
0007                          [illegible]B120,B130,B230
0008                          [illegible]WE,CON,IXST,C1,C2,C3
0009                          [illegible]
0010                          [illegible]
0011                          [illegible]
0012                          [illegible]
0013                          [illegible]
0014                          [illegible]
0015                          [illegible]
0016                          [illegible]
0017                          [illegible]
0018                          [illegible]
0019                          [illegible]
0020                          [illegible]
0021                          [illegible]
0022                          [illegible]
0023                          [illegible]
0024                          [illegible]
0025                          [illegible]
0026                          [illegible]
0027                          [illegible]
0028                          [illegible]
0029                          [illegible]
0030                          [illegible]
0031                          [illegible]
0032                          [illegible]
0033                          [illegible]
0034                          [illegible]

*OPTIONS IN EFFECT*  [illegible]NOMAP,NOTEST
*OPTIONS IN EFFECT*  [illegible]
*STATISTICS*  [illegible]SIZE = 0007BC
*STATISTICS*  [illegible]
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0002
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```
 *OPTIONS IN EFFECT*                  SOURCE,EBCDIC,NOSOURCE,NOLIST,NODECK,LOAD,NOMAP,NOTEST
 *OPTIONS IN EFFECT*                  LINECNT =      56
 *STATISTICS*                         PROGRAM SIZE = 000344
 *STATISTICS*
 *STATISTICS*
                                                                        4.35
/DATA
00A1F8 BYTES USED
EXECUTION BEGINS
TIME INCREMENT= 0.0005  FINAL TIME =10.0000
```

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